

US008293328B2

(12) **United States Patent**
Chen et al.

(10) **Patent No.:** **US 8,293,328 B2**
(45) **Date of Patent:** **Oct. 23, 2012**

(54) **ENHANCED COPPER GROWTH WITH ULTRATHIN BARRIER LAYER FOR HIGH PERFORMANCE INTERCONNECTS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1623 days.

(21) Appl. No.: **11/470,915**

(22) Filed: **Sep. 7, 2006**

(65) **Prior Publication Data**

US 2007/0003698 A1 Jan. 4, 2007

Related U.S. Application Data

(63) Continuation of application No. 10/199,415, filed on Jul. 18, 2002, now abandoned.

(60) Provisional application No. 60/346,086, filed on Oct. 26, 2001.

(51) **Int. Cl.**
C23C 16/00 (2006.01)

(52) **U.S. Cl.** **427/255.28**; 427/255.23; 427/255.36; 427/255.391; 427/255.394

(58) **Field of Classification Search** 427/255.23, 427/255.28, 255.36, 255.391, 255.394
See application file for complete search history.

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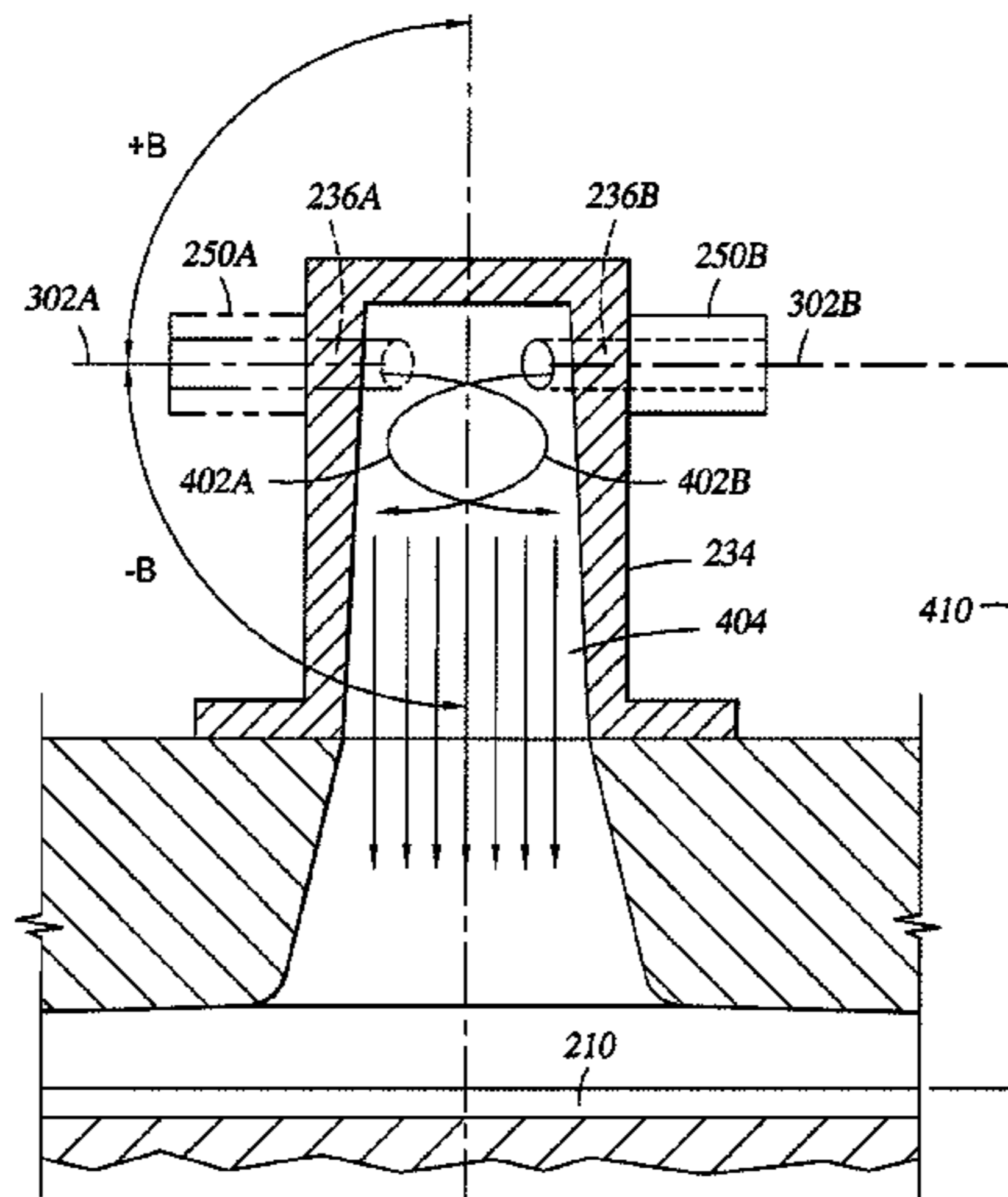
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(57) **ABSTRACT**

A method for depositing a refractory metal nitride barrier layer having a thickness of about 20 angstroms or less is provided. In one aspect, the refractory metal nitride layer is formed by introducing a pulse of a metal-containing compound followed by a pulse of a nitrogen-containing compound. The refractory metal nitride barrier layer provides adequate barrier properties and allows the grain growth of the first metal layer to continue across the barrier layer into the second metal layer thereby enhancing the electrical performance of the interconnect.

20 Claims, 8 Drawing Sheets



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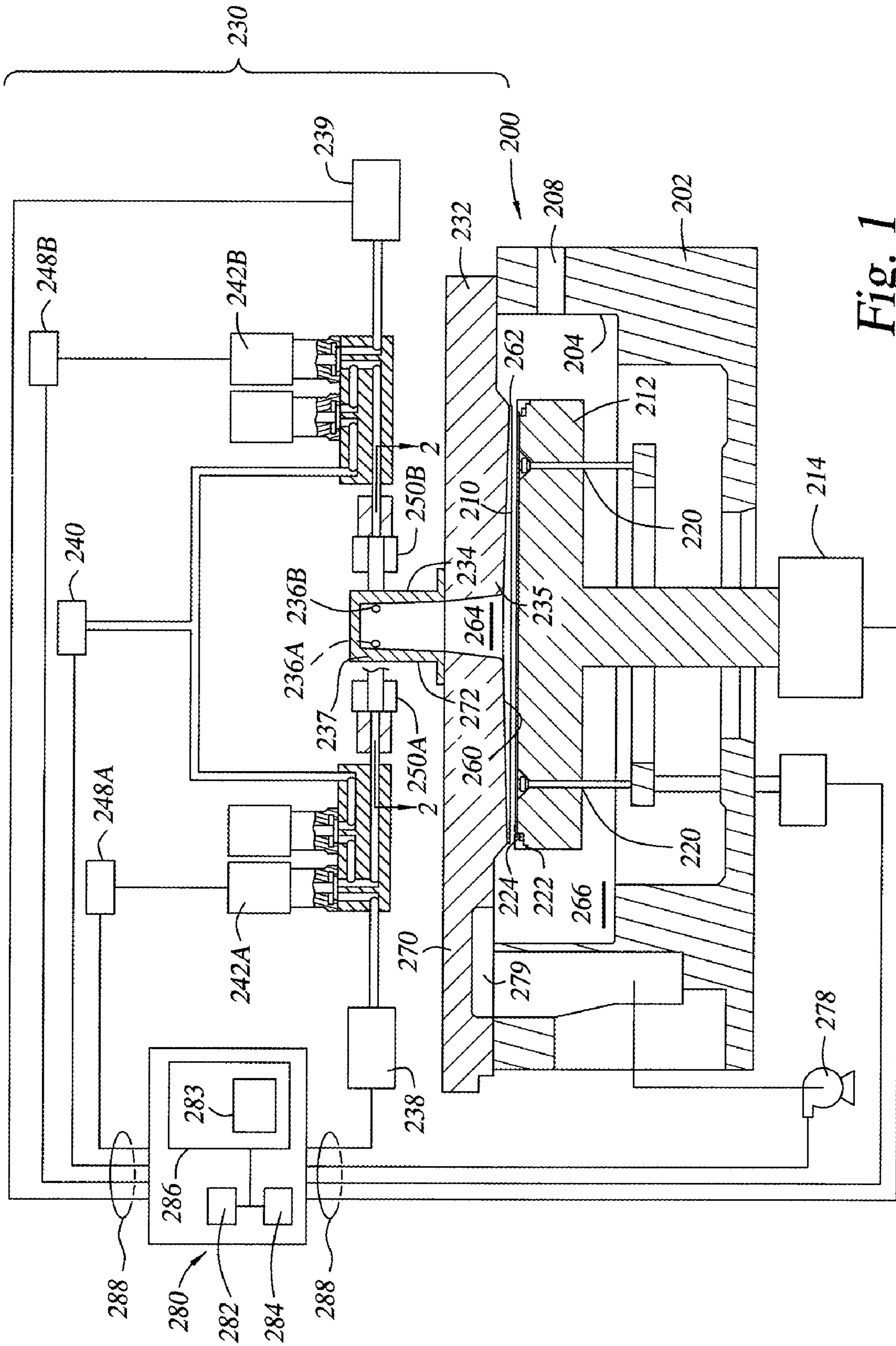


Fig. 1

Fig. 2A

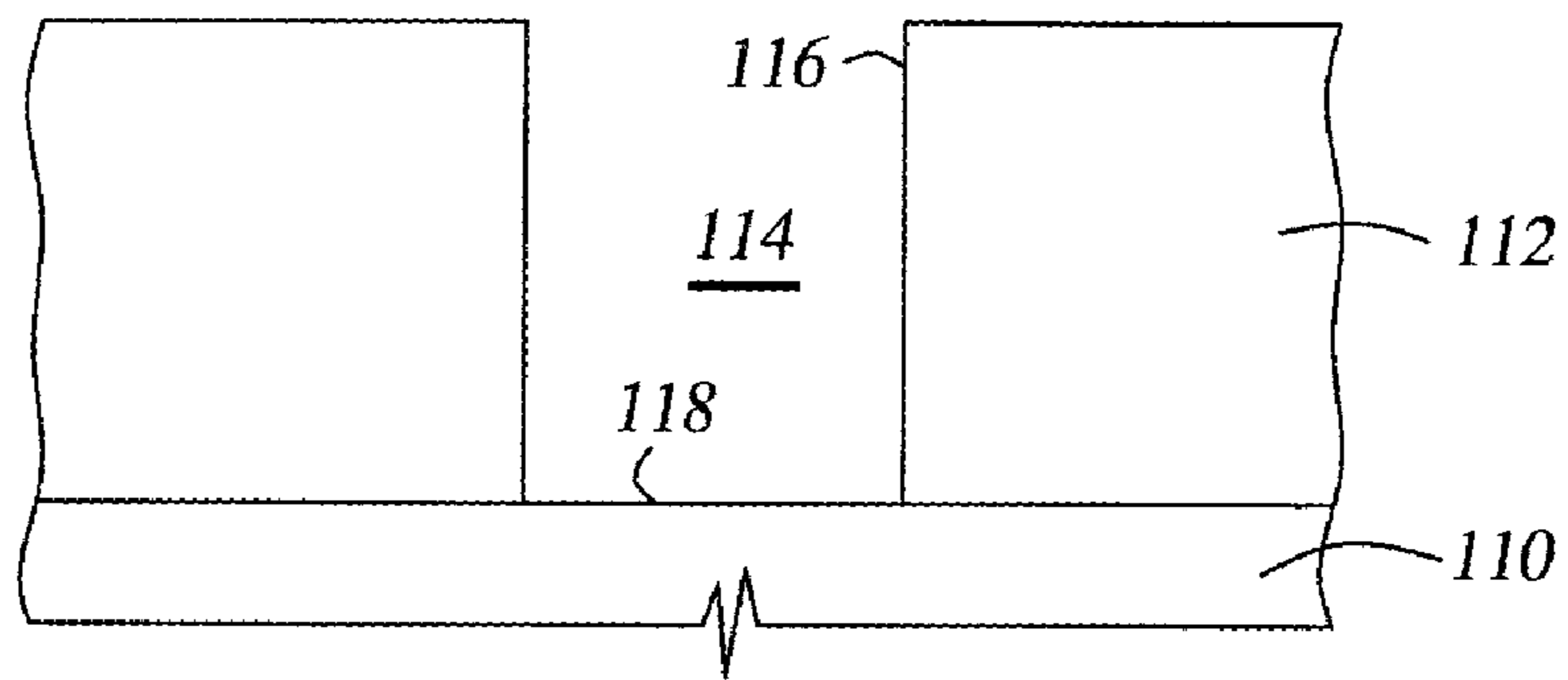


Fig. 2B

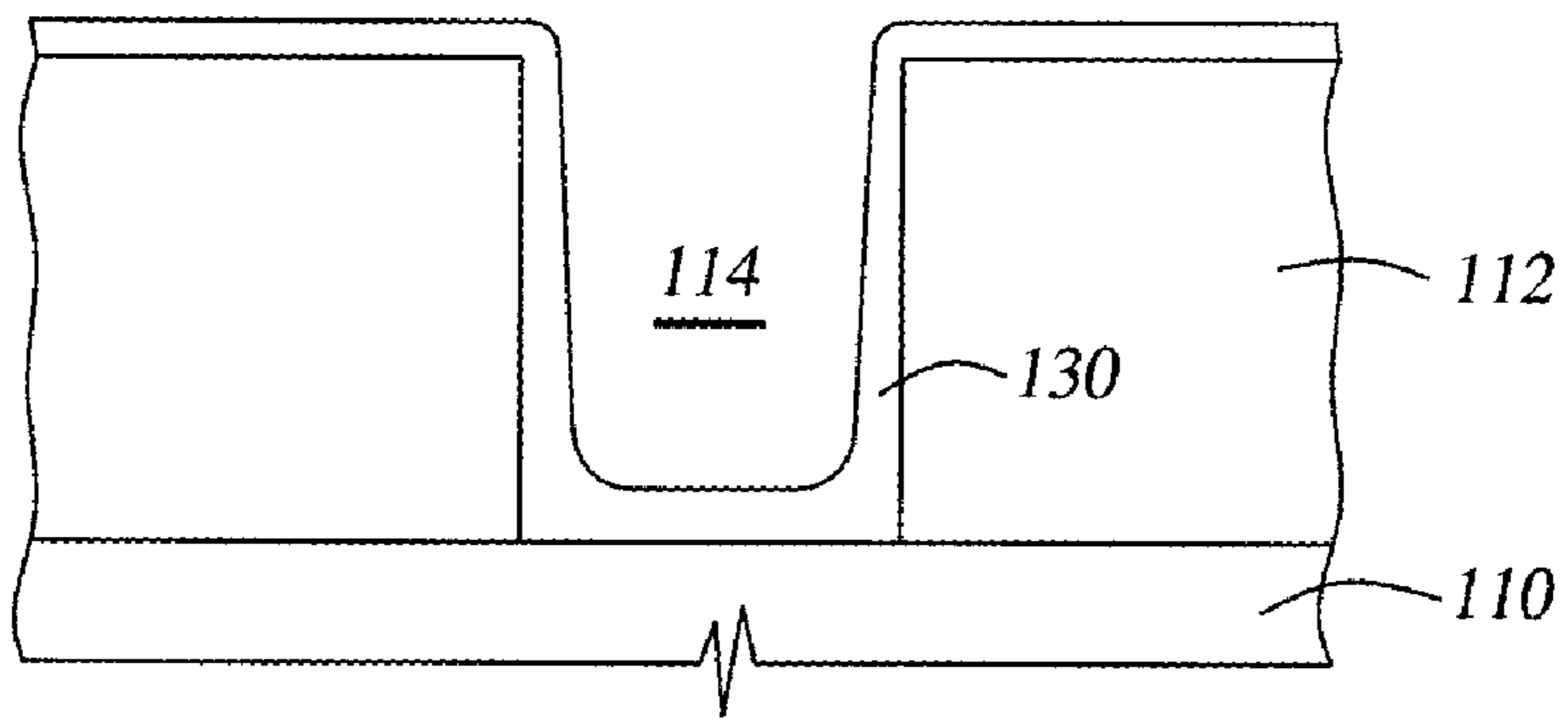


Fig. 2C

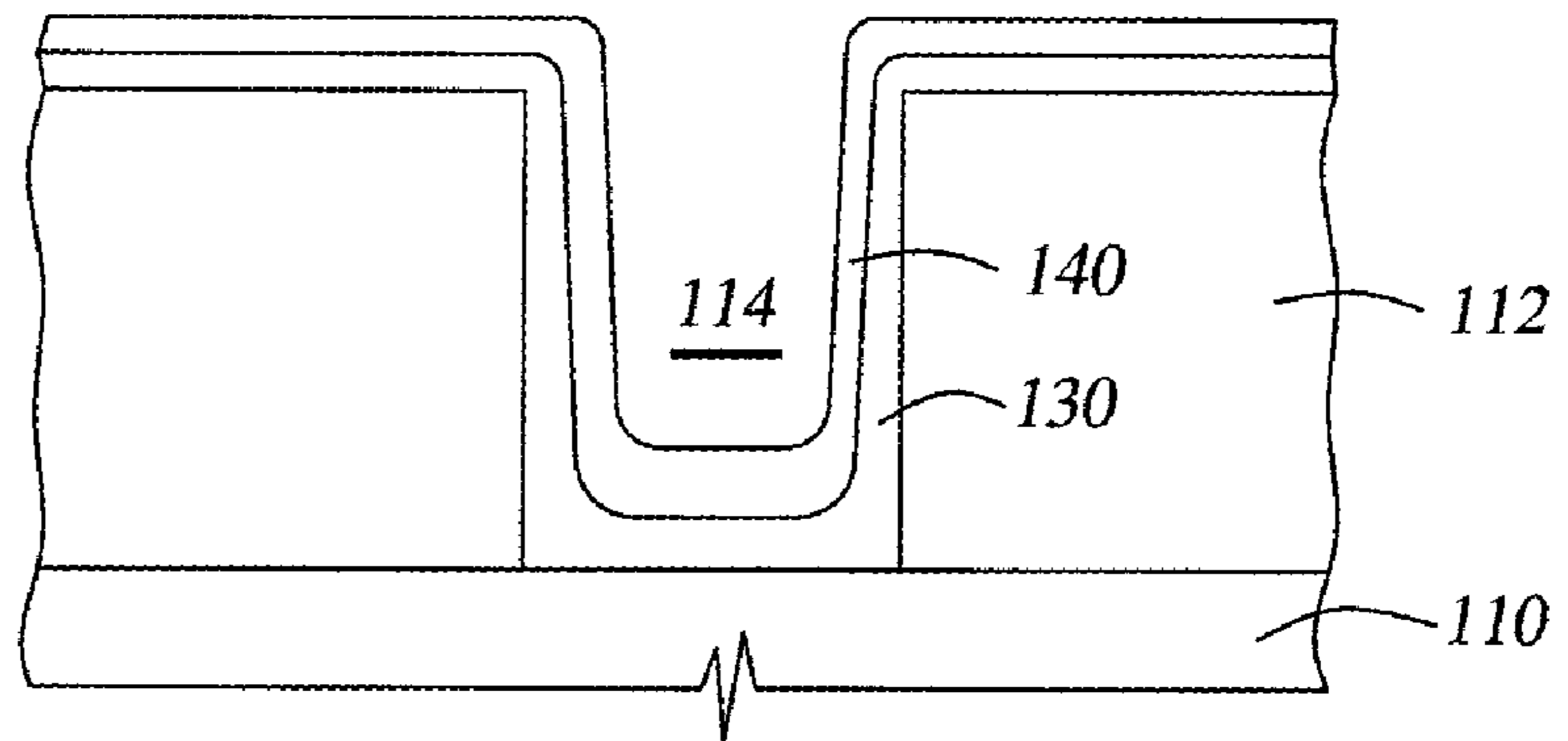
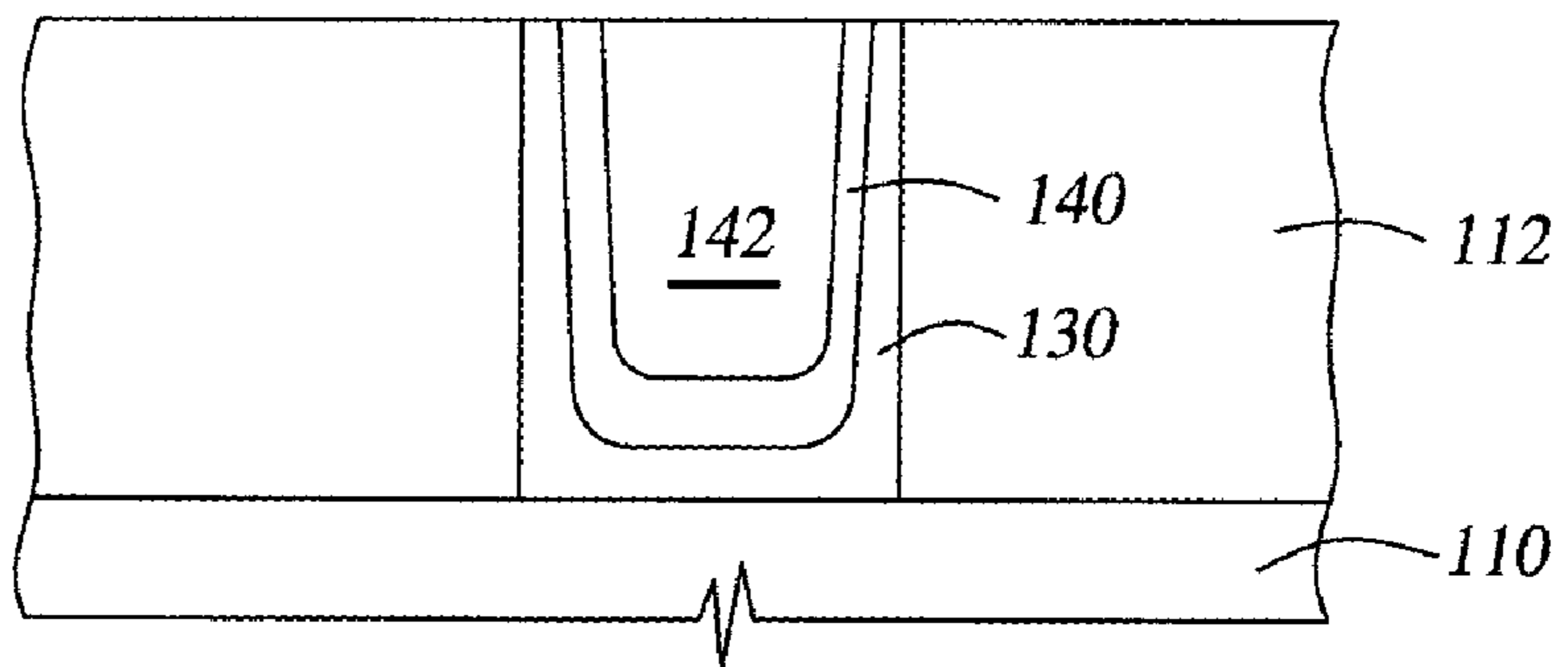


Fig. 2D



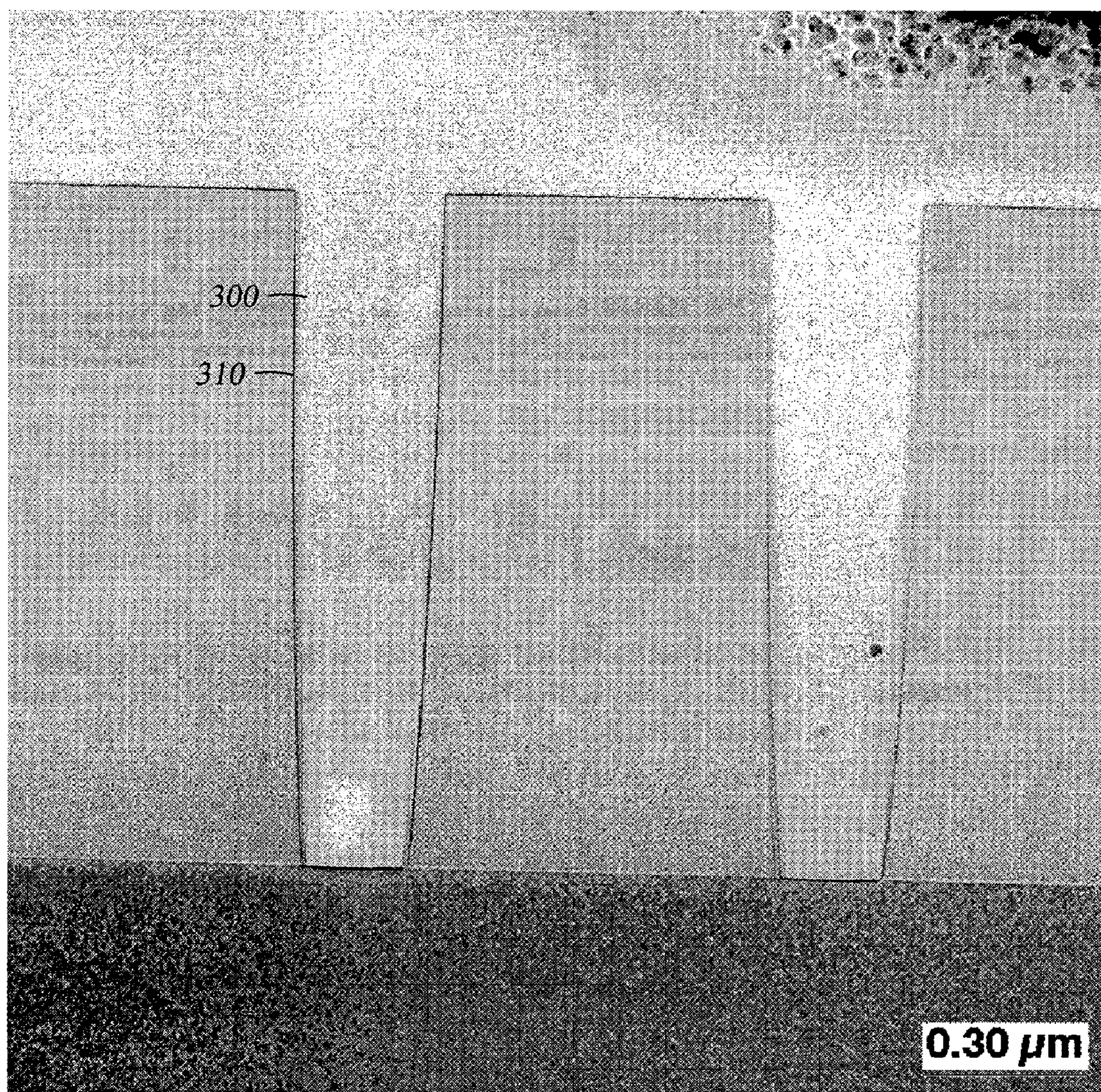


Fig. 3

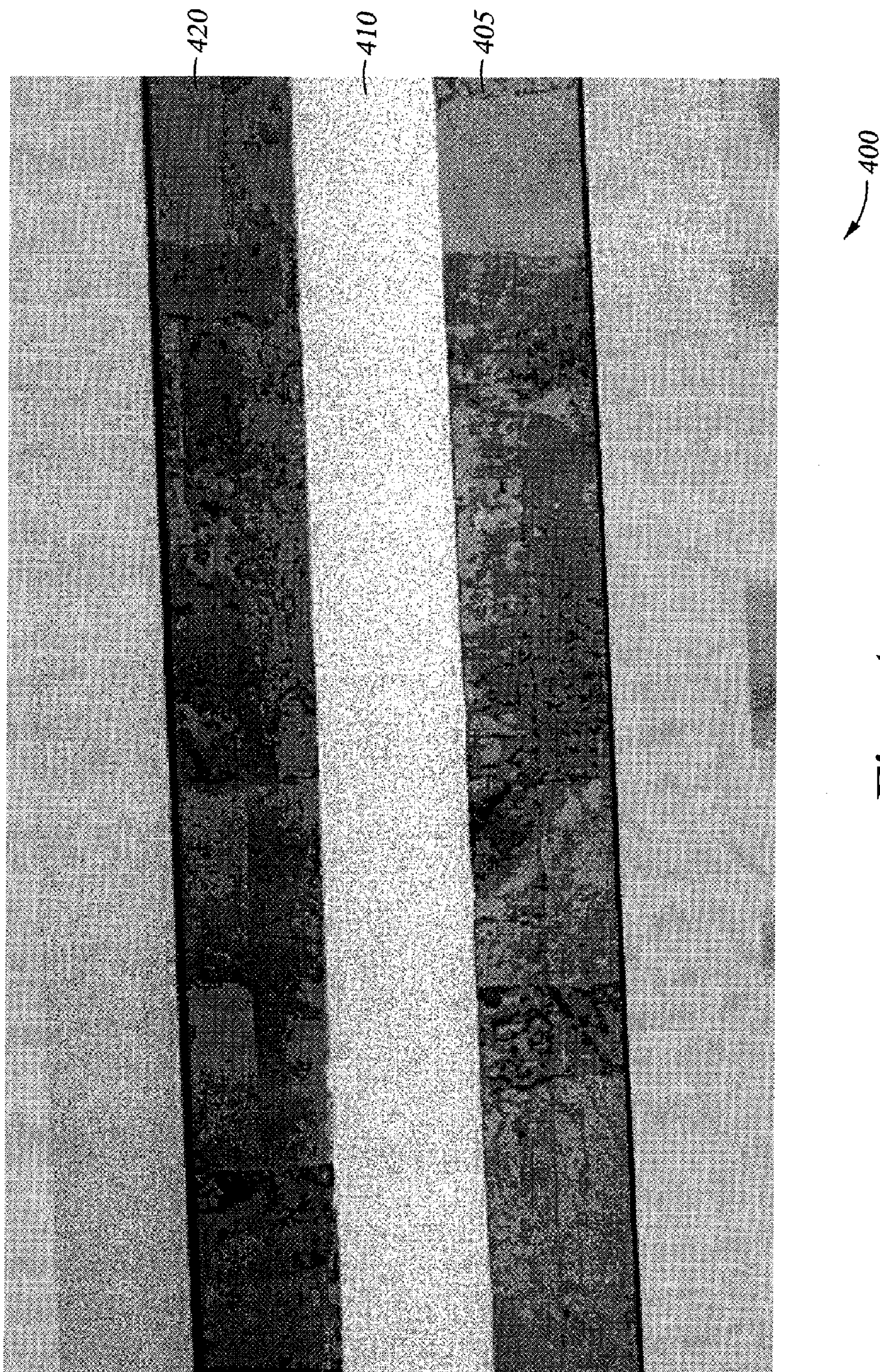
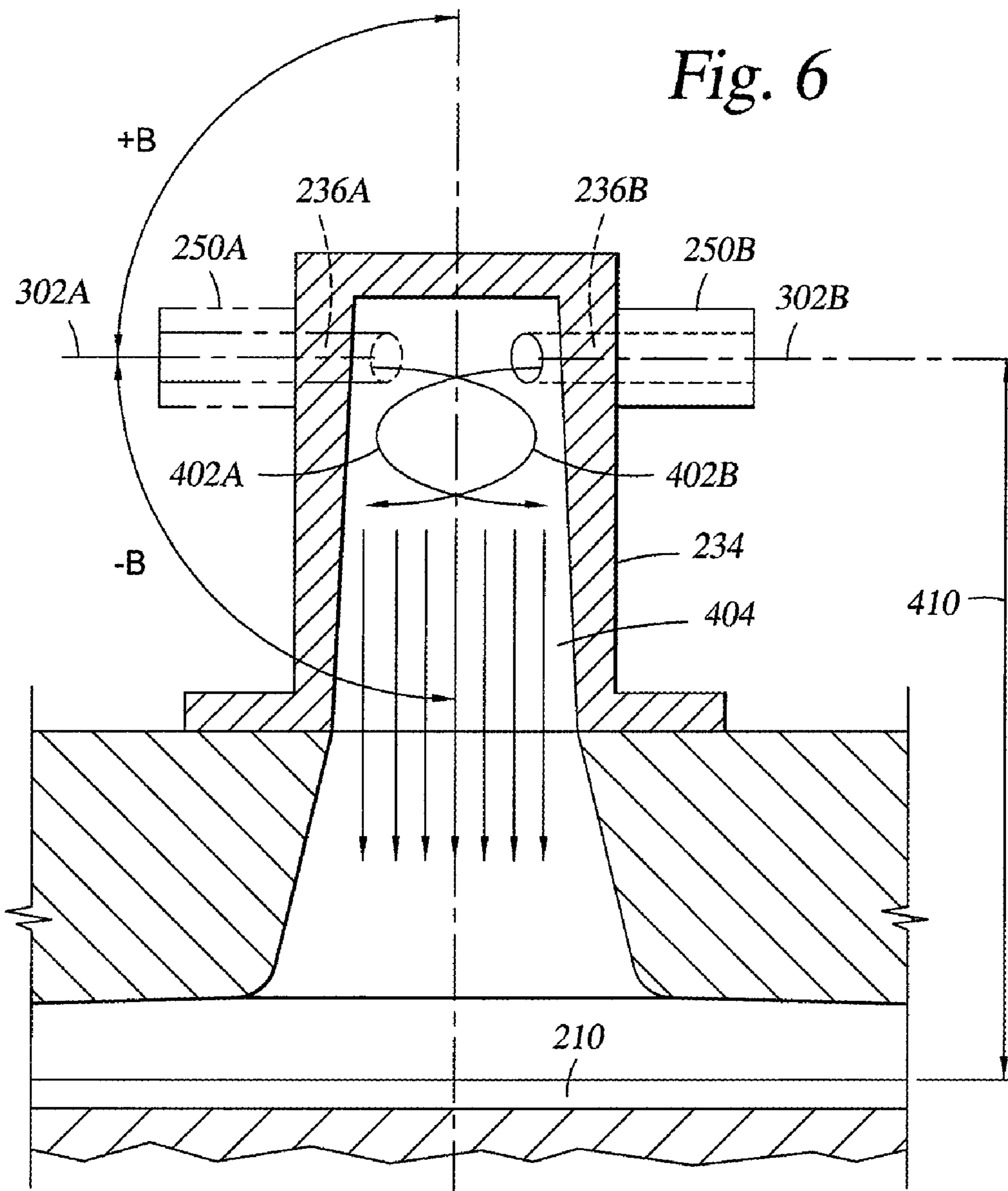
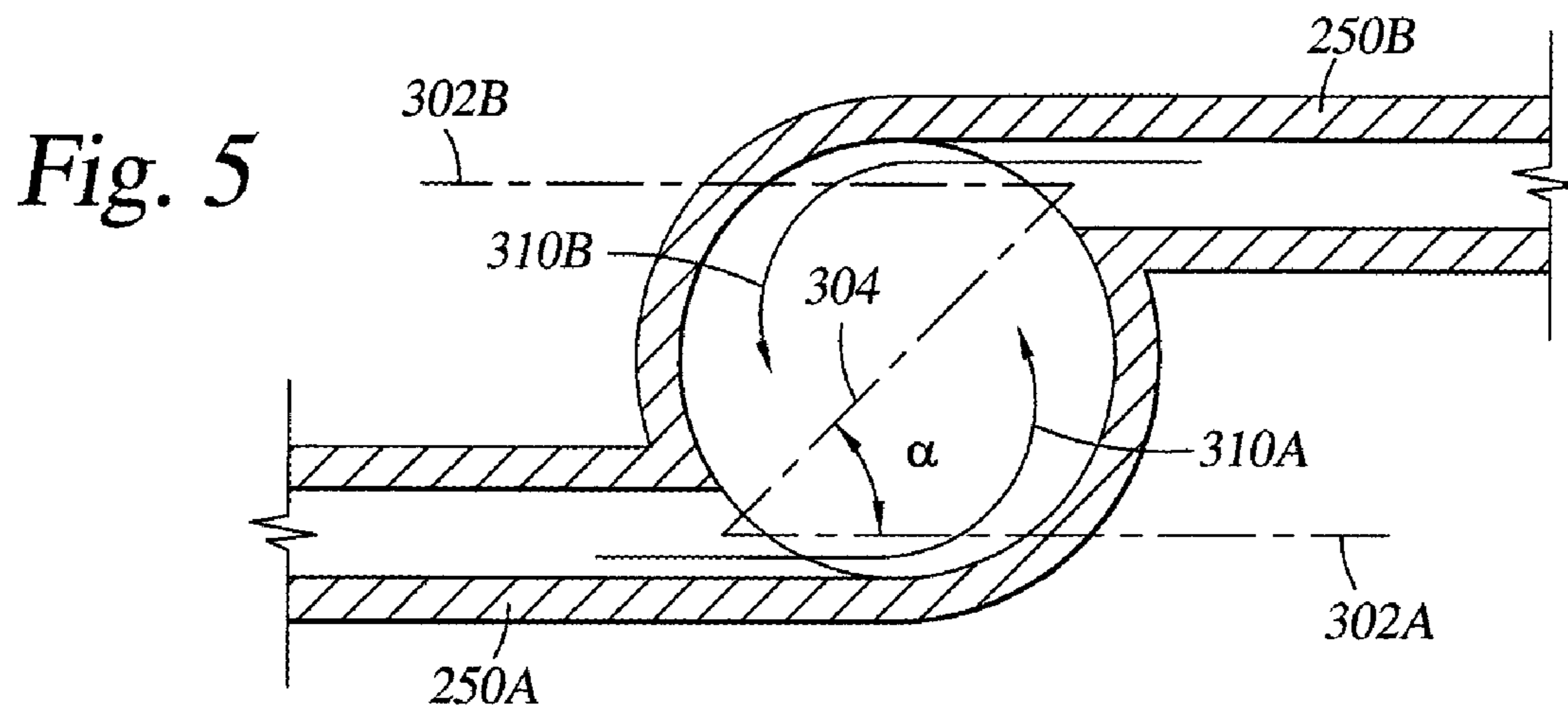


Fig. 4



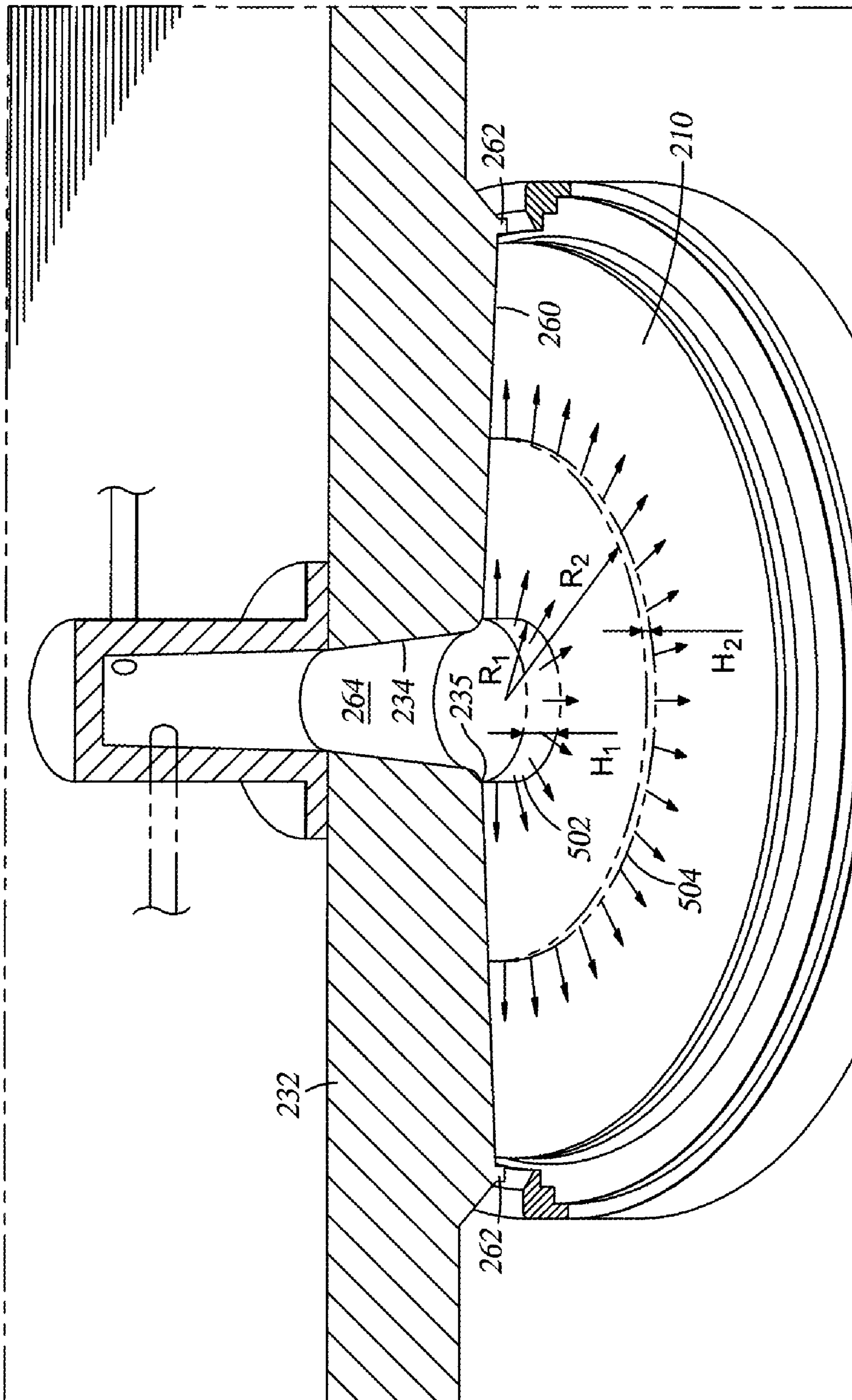


Fig. 7

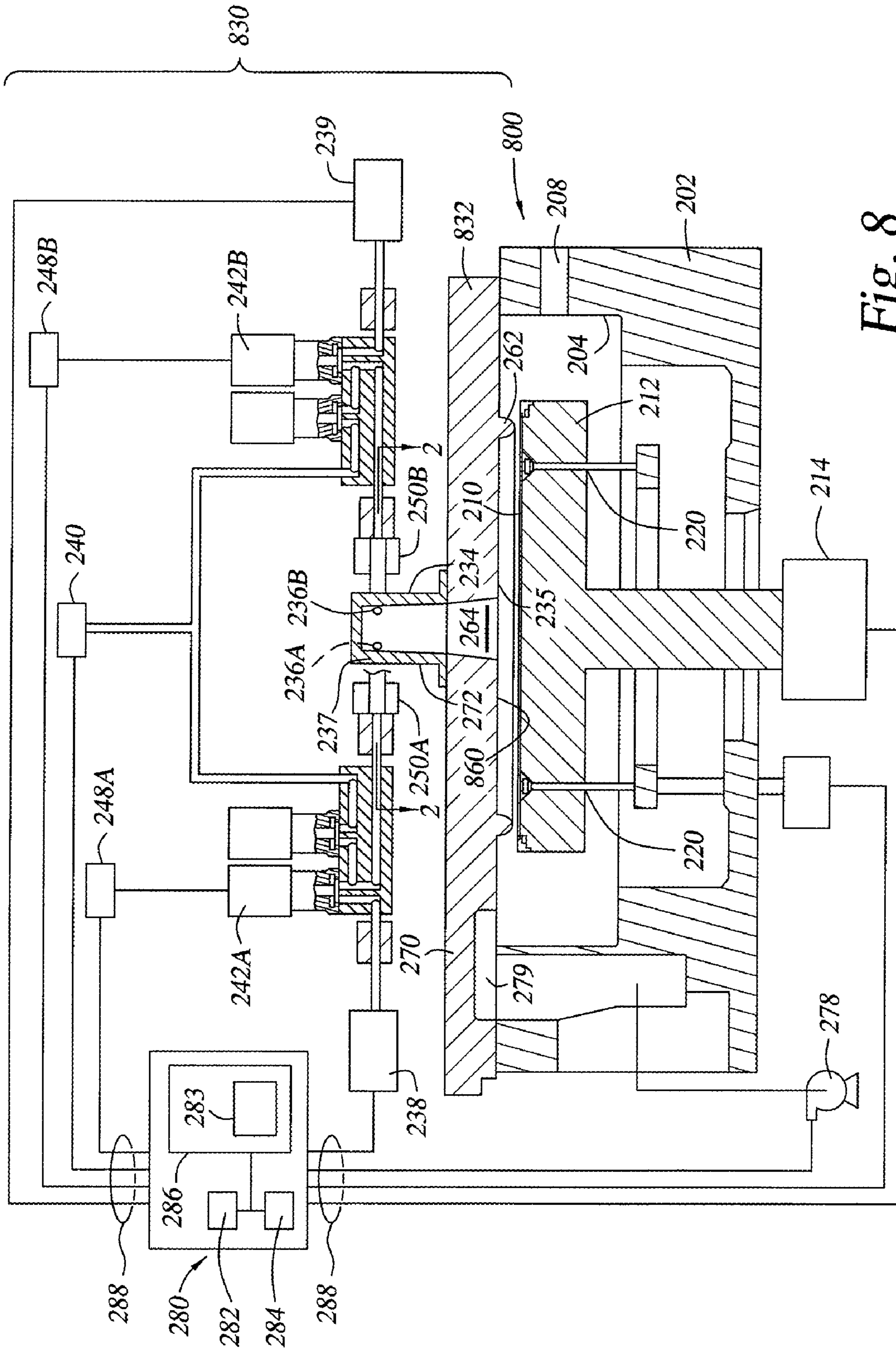


Fig. 8

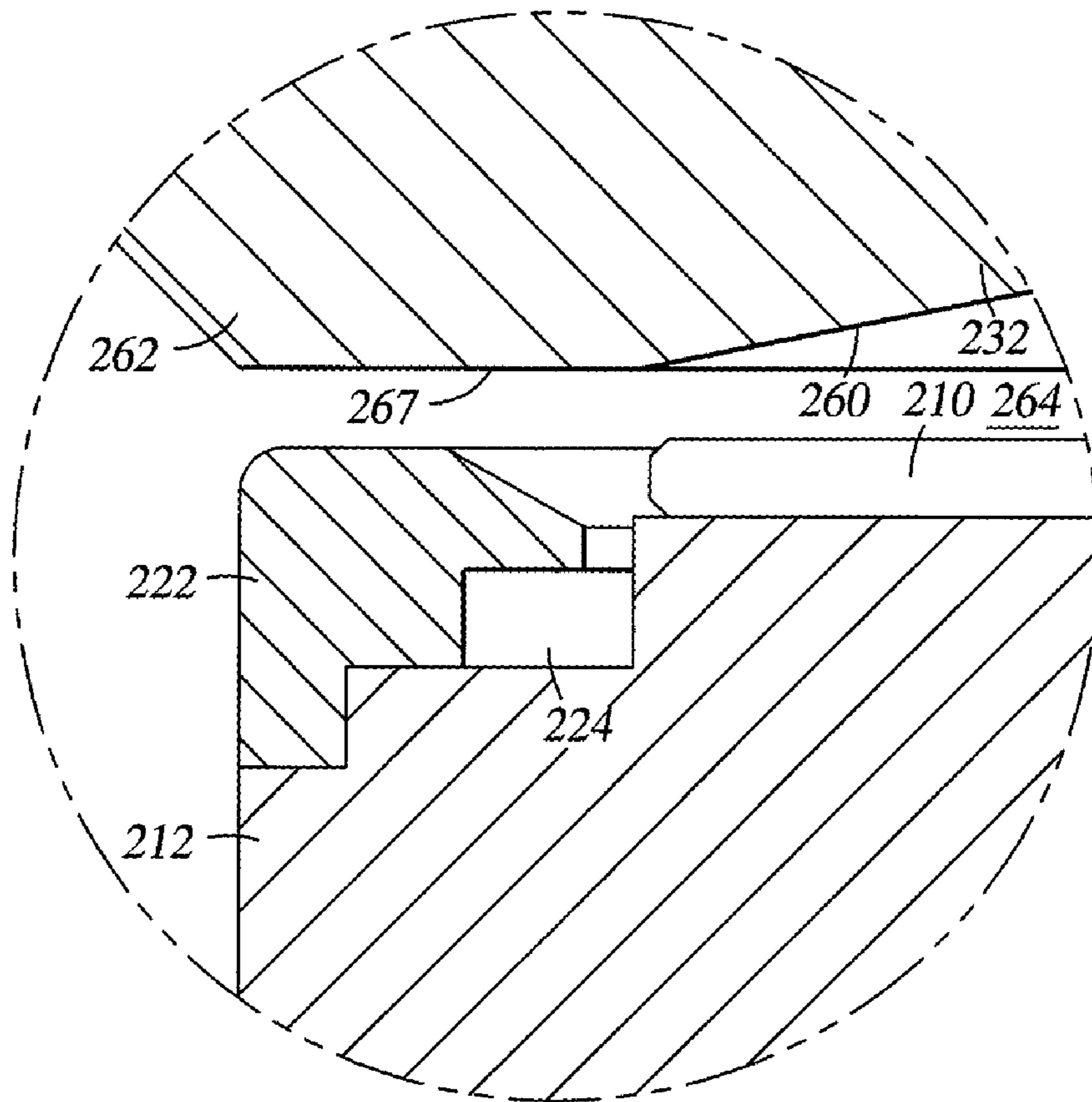


Fig. 9A

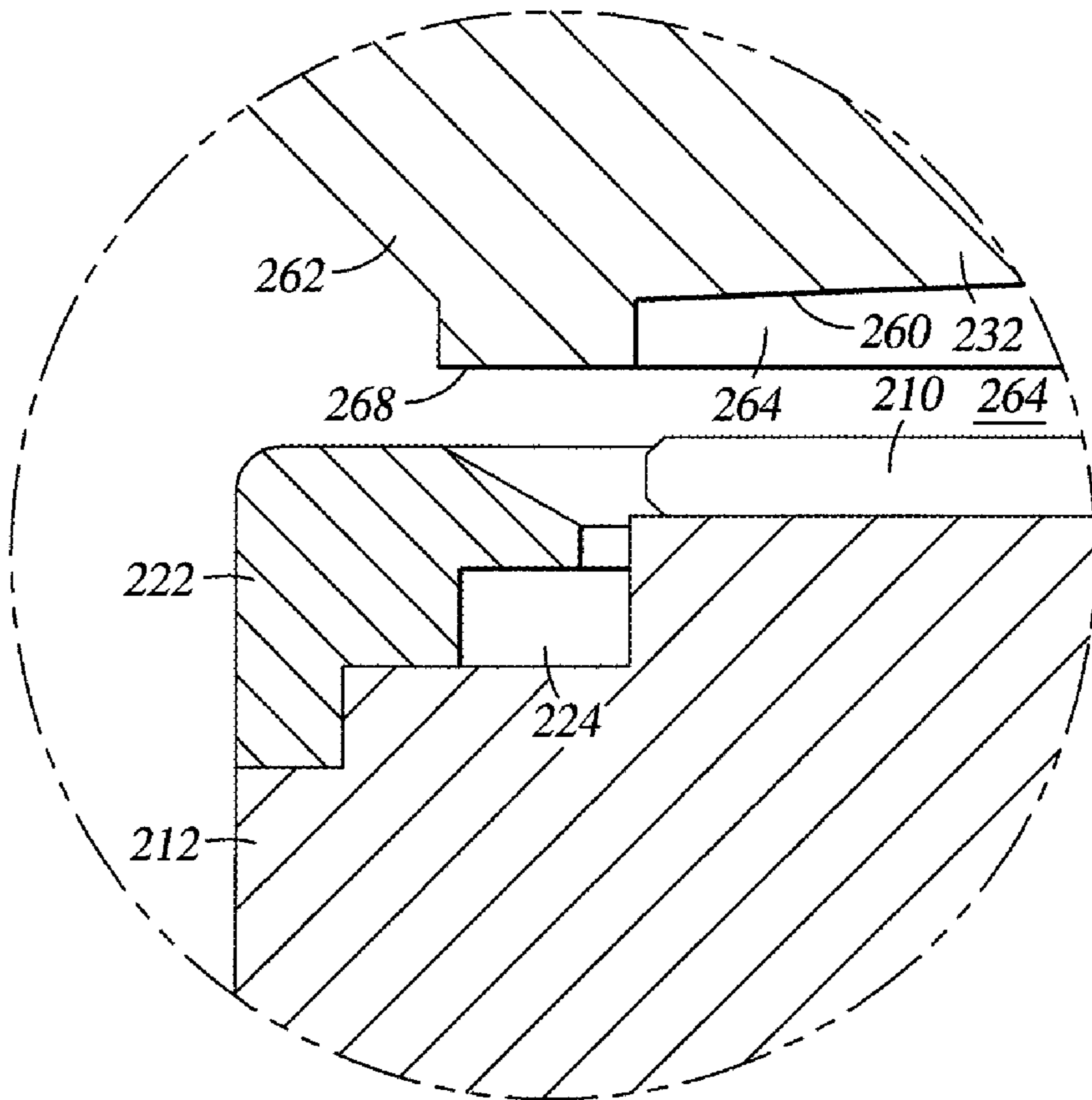


Fig. 9B

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ENHANCED COPPER GROWTH WITH ULTRATHIN BARRIER LAYER FOR HIGH PERFORMANCE INTERCONNECTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 10/199,415 filed Jul. 18, 2002, now abandoned, which is incorporated by reference herein, and which application claims benefit of U.S. Provisional Patent Application Ser. No. 60/346,086, filed Oct. 26, 2001, which is incorporated by reference herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

Embodiments of the present invention relate to a method for manufacturing integrated circuit devices. More particularly, embodiments of the invention relate to forming thin barrier layers using cyclic or atomic layer deposition.

2. Description of the Related Art

Copper has recently become a choice metal for filling sub-micron high aspect ratio, interconnect features because copper and its alloys have lower resistivities than aluminum. However, copper and its alloys have a propensity to diffuse into surrounding materials such as silicon oxide, silicon, and other dielectric materials for example, causing an increase in the contact resistance of the circuit. Copper and its alloys also have a propensity to diffuse into surrounding elements such as transistor gates, capacitor dielectrics, transistor wells, transistor channels, electrical barrier regions, interconnects, among other known elements of integrated circuits.

Barrier layers are, therefore, deposited prior to copper metallization to prevent or impede the diffusion of copper atoms. Barrier layers typically consist of a refractory metal such as tungsten, titanium, tantalum, and nitrides thereof, which all have a greater resistivity than copper. Of this group, tantalum nitride is one of the most desirable elements for use as a barrier layer because it has one of the lowest resistivities of refractory metal nitrides and makes a good adhesion layer for copper metallization.

To deposit a barrier layer within a feature, the barrier layer must be deposited on the bottom of the feature as well as the sidewalls thereof. Therefore, the additional amount of the barrier layer on the bottom of the feature not only increases the overall resistance of the feature, but also forms an obstruction between higher and lower metal interconnects of a multi-layered interconnect structure.

It is especially difficult to deposit a suitable barrier layer in features having aspect ratios greater than about 3:1 using conventional deposition techniques. Usually, the barrier layer bridges the opening of the narrow features resulting in the formation of one or more voids or discontinuities within the feature. Since voids increase the resistance and reduce the electromigration resistance of the feature, features having voids make poor and unreliable electrical contacts.

There is a need, therefore, for an improved method for depositing a thin, conformal barrier layer in low aspect ratio features.

SUMMARY OF THE INVENTION

A method for depositing a conformal refractory metal nitride layer having a thickness of about 20 angstroms or less is provided. The refractory metal nitride layer is formed by introducing a pulse of a metal-containing compound fol-

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lowed by a pulse of a nitrogen-containing compound. The refractory metal nitride layer may further be formed by introducing a pulse of a silicon-containing compound. The refractory metal nitride layer provides excellent barrier properties and permits the continuous, uninterrupted growth of a higher level conductive metal layer on a lower level conductive metal layer. In one aspect, the conductive metal layers each contain copper or copper alloys, and the refractory metal nitride layer contains tantalum nitride. In another aspect, the refractory metal layer contains titanium silicon nitride.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present invention are attained and can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to the embodiments thereof which are illustrated in the appended drawings.

It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIG. 1 illustrates a schematic, partial cross section of an exemplary processing chamber 200 for use in a method of forming a barrier layer according to each of the embodiments of the present invention.

FIGS. 2A-2D illustrate steps for forming a metal interconnect in accordance with embodiments of a cycled deposition technique described herein.

FIG. 3 is a TEM image of a metal interconnect having a barrier layer deposited in accordance with embodiments of a cyclical deposition technique described herein.

FIG. 4 is a TEM image showing a continuous copper grain growth across a barrier layer deposited in accordance with embodiments of a cyclical deposition technique described herein.

FIG. 5 is a top cross-sectional view of one embodiment of the expanding channel of the chamber lid of FIG. 1.

FIG. 6 is a cross-sectional view of the expanding channel of the chamber lid of FIG. 1.

FIG. 7 is a schematic cross-sectional view illustrating the flow of a gas at two different positions between the surface of a substrate and the bottom surface of the chamber lid of FIG. 1.

FIG. 8 is a schematic cross-sectional view of another embodiment of a chamber including a gas delivery apparatus adapted for atomic layer deposition.

FIG. 9A is a schematic cross-sectional view of one embodiment of the choke of the chamber lid.

FIG. 9B is a cross-sectional view of another embodiment of the choke of the chamber lid.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Embodiments of the present invention generally provide a method of forming a barrier layer through which conductive metal can be grown. In one embodiment, a cyclical deposition process is used to form a refractory metal nitride layer having a thickness less than about 20 angstroms. In one aspect of this embodiment, the refractory metal nitride layer is a tantalum nitride (TaN) layer that is preferably about 10 angstroms thick. In another aspect of this embodiment, the refractory metal nitride layer is a ternary material, such as titanium silicon nitride, for example.

The barrier layers deposited according to the cyclical deposition techniques described herein provide excellent barrier

properties and permit the continuous growth of conductive metal layers thereon. The barrier layers are particularly useful between higher and lower level conductive metal interconnects. The barrier layers significantly enhance the metal interconnect electrical performance by lowering the overall electrical resistance of the feature and also providing good device reliability.

The barrier layers deposited according to the cyclical deposition methods described herein show evidence of an epitaxial growth phenomenon. In other words, the barrier layers take on the same or substantially the same crystallographic characteristics as the underlying layer. As a result, a substantially single crystal is grown such that there is no void formation at an interface between the barrier layer and the underlying layer. Likewise, subsequent metal layers deposited over the barrier layers exhibit the same or substantially the same epitaxial growth characteristics that continue the formation of the single crystal. Accordingly, no void formation is produced at this interface. The resulting structure resembling a single crystal eliminates voids formation, thereby substantially increasing device reliability. The single crystal structure also reduces the overall resistance of the interconnect feature while still providing excellent barrier properties. Furthermore, it is believed that the single crystalline growth reduces the susceptibility of electromigration and stress migration due to the conformal and uniform crystalline orientation across the interconnect material interfaces.

A TaN barrier layer having a thickness of about 20 angstroms or less, about 10 angstroms in at least one embodiment, is deposited by providing one or more pulses of a tantalum-containing compound at a flow rate between about 100 sccm and about 1,000 sccm for a time period of about 1.0 second or less and one or more pulses of a nitrogen-containing compound at a flow rate between about 100 sccm and about 1,000 sccm for a time period of about 1.0 second or less to a reaction zone having a substrate disposed therein. Exemplary tantalum-containing compounds include pentaethylmethylamino-tantalum (PEMAT), pentadiethylamino-tantalum (PDEAT), pentadimethylamino-tantalum (PDMAT) and any derivatives of PEMAT, PDEAT, and PDMAT. Exemplary tantalum-containing compounds also include t-butylimino tris(diethylamino)tantalum (TBTDET), t-butylimino tris(dimethylamino)tantalum (TBTDMT), bis(cyclopentadienyl)tantalum trihydride, bis(methylcyclopentadienyl)tantalum trihydride, and tantalum halides, TaX_5 , where X is fluorine (F), bromine (Br) or chlorine (Cl), and/or derivatives thereof. Exemplary nitrogen-containing compounds include nitrogen gas, ammonia, hydrazine, methylhydrazine, dimethylhydrazine, t-butylhydrazine, phenylhydrazine, azotert-butane, ethylazide, and derivatives thereof.

It is to be understood that these compounds or any other compound not listed above may be a solid, liquid, or gas at room temperature. For example, PDMAT is a solid at room temperature and TBTDET is a liquid at room temperature. Accordingly, the non-gas phase precursors are subjected to a sublimation or vaporization step, which are both well known in the art, prior to introduction into the processing chamber. A carrier gas, such as argon, helium, nitrogen, hydrogen, or a mixture thereof, may also be used to help deliver the compound into the processing chamber, as is commonly known in the art.

Each pulse is performed sequentially, and is accompanied by a separate flow of non-reactive gas at a rate between about 200 sccm and about 1,000 sccm. The separate flow of non-reactive gas may be pulsed between each pulse of the reactive compounds or the separate flow of non-reactive gas may be introduced continuously throughout the deposition process.

The separate flow of non-reactive gas, whether pulsed or continuous, serves to remove any excess reactants from the reaction zone to prevent unwanted gas phase reactions of the reactive compounds, and also serves to remove any reaction by-products from the processing chamber, similar to a purge gas. In addition to these services, the continuous separate flow of non-reactive gas helps deliver the pulses of reactive compounds to the substrate surface similar to a carrier gas. The term "non-reactive gas" as used herein refers to a single gas or a mixture of gases that does not participate in the metal layer formation. Exemplary non-reactive gases include argon, helium, nitrogen, hydrogen, and combinations thereof.

In another embodiment, a ternary barrier layer having a thickness less than about 20 angstroms, preferably about 10 angstroms in at least one embodiment, is deposited by providing one or more pulses of a refractory metal-containing compound at a flow rate between about 10 sccm and about 1,000 sccm, one or more pulses of a nitrogen-containing compound at a flow rate between about 100 sccm and about 5,000 sccm, and one or more pulses of a silicon-containing compound at a flow rate between about 5 sccm and about 500 sccm. Each pulse lasts about 1.0 second or less, and can be adjusted to provide a desirable composition, silicon incorporation level, thickness, density, and step coverage of the refractory metal silicon nitride layer. A "ternary barrier layer" as used herein refers to a material having a composition that includes three major elements, such as titanium, nitrogen and silicon, for example.

Exemplary titanium-containing compounds include tetrakis(dimethylamino)titanium (TDMAT), tetrakis(ethylmethylamino)titanium (TEMAT), tetrakis(diethylamino)titanium (TDEAT), titanium tetrachloride ($TiCl_4$), titanium iodide (TiI_4), titanium bromide ($TiBr_4$), and other titanium halides. Exemplary silicon-containing compounds include silane, disilane, methylsilane, dimethylsilane, chlorosilane, dichlorosilane, and trichlorosilane. Exemplary nitrogen-containing compounds include nitrogen gas, ammonia, hydrazine, methylhydrazine, dimethylhydrazine, t-butylhydrazine, phenylhydrazine, azoisobutane, ethylazide, and derivatives thereof.

As mentioned above, these compounds or any other compound not listed above may be a solid, liquid, or gas at room temperature. The non-gas phase precursors must be subjected to a sublimation or vaporization step, which are both well known in the art, prior to introduction into the processing chamber. A carrier gas, such as argon, helium, nitrogen, hydrogen, or a mixture thereof, may also be used to help deliver the compound into the processing chamber, as is commonly known in the art.

Similar to the process described above, each pulse of compound is performed sequentially, and is accompanied by a separate flow of non-reactive gas. The separate flow of non-reactive gas may be pulsed between each pulse of reactive compound or the separate flow of non-reactive gas may be introduced continuously throughout the deposition process. Exemplary non-reactive gases include argon, helium, nitrogen, hydrogen, and combinations thereof.

A "compound" is intended to include one or more precursors, reductants, reactants, and catalysts. Each compound may be a single compound or a mixture/combination of two or more compounds.

A "thin layer" as used herein refers to a layer of material deposited on a substrate surface having a thickness of about 20 angstroms or less, such as about 10 angstroms. A "feature" as used herein refers to a via, contact, line, or any other interconnect facet, e.g., vertical or horizontal interconnect, having an aspect ratio (height to width ratio) of about 4:1 or

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greater. A “substrate surface”, as used herein, refers to any substrate surface upon which film processing is performed. For example, a substrate surface may include silicon, silicon oxide, doped silicon, germanium, gallium arsenide, glass, sapphire, and any other materials such as metals, metal alloys, and other conductive materials, depending on the application. A substrate surface may also include dielectric materials such as silicon dioxide and carbon doped silicon oxides.

“Cyclical deposition” as used herein refers to the sequential introduction of two or more compounds to deposit a thin layer on a substrate surface. The two or more compounds are sequentially introduced into a reaction zone of a processing chamber. Each compound is separated by a time delay/pause to allow each compound to adhere and/or react on the substrate surface. In one aspect, a first compound or compound A is dosed/pulsed into the reaction zone followed by a first time delay/pause. Next, a second compound or compound B is dosed/pulsed into the reaction zone followed by a second time delay. When a ternary material is desired, such as titanium silicon nitride, for example, a third compound (C), is dosed/pulsed into the reaction zone followed by a third time delay. These sequential tandems of a pulse of reactive compound followed by a time delay may be repeated indefinitely until a desired film or film thickness is formed on the substrate surface.

A “pulse/dose” as used herein is intended to refer to a quantity of a particular compound that is intermittently or non-continuously introduced into a reaction zone of a processing chamber. The quantity of a particular compound within each pulse may vary over time, depending on the duration of the pulse. A particular compound may include a single compound or a mixture/combination of two or more compounds.

A “reaction zone” is intended to include any volume that is in fluid communication with a substrate surface being processed. The reaction zone may include any volume within a processing chamber that is between a gas source and the substrate surface. For example, the reaction zone includes any volume downstream of a dosing valve in which a substrate is disposed.

The durations for each pulse/dose are variable and may be adjusted to accommodate, for example, the volume capacity of the processing chamber as well as the capabilities of a vacuum system coupled thereto. Additionally, the dose time of a compound may vary according to the flow rate of the compound, the pressure of the compound, the temperature of the compound, the type of dosing valve, the type of control system employed, as well as the ability of the compound to adsorb onto the substrate surface. Dose times may also vary based upon the type of layer being formed and the geometry of the device being formed.

Typically, the duration for each pulse/dose or “dose time” is typically about 1.0 second or less. However, a dose time can range from microseconds to milliseconds to seconds, and even to minutes. In general, a dose time should be long enough to provide a volume of compound sufficient to adsorb/chemisorb onto substantially the entire surface of the substrate and form a layer of the compound thereon.

FIG. 1 illustrates a schematic, partial cross section of an exemplary processing chamber 200 for use in a method of forming a barrier layer according to each of the embodiments of the present invention. Such a processing chamber 200 is available from Applied Materials, Inc. located in Santa Clara, Calif., and a brief description thereof follows. A more detailed description may be found in commonly assigned U.S. patent application Ser. No. 10/032,284, entitled “Gas

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Delivery Apparatus and Method For Atomic Layer Deposition”, filed on Dec. 21, 2001, which is incorporated herein by reference.

FIG. 5 is a top cross-sectional view of one embodiment of the expanding section 234 of the chamber lid 232 of FIG. 1. Each gas conduit 250A, 250B may be positioned at an angle α from the center line 302A, 302B of the gas conduit 250A, 250B and from a radius line 304 from the center of the expanding channel 234. Entry of a gas through the gas conduit 250A, 250B preferably positioned at an angle α (i.e., when $\alpha > 0^\circ$) causes the gas to flow in a circular direction as shown by arrow 310A (or 310B). Providing gas at an angle α as opposed to directly straight-on to the walls of the expanding channel (i.e., when $\alpha = 0^\circ$) helps to provide a more laminar flow through the expanding channel 234 rather than a turbulent flow. It is believed that a laminar flow through the expanding channel 234 results in an improved purging of the inner surface of the expanding channel 234 and other surfaces of the chamber lid 232. In comparison, a turbulent flow may not uniformly flow across the inner surface of the expanding channel 234 and other surfaces and may contain dead spots or stagnant spots in which there is no gas flow. In one aspect, the gas conduits 250A, 250B and the corresponding gas inlets 236A, 236B are spaced out from each other and direct a flow in the same circular direction (i.e., clockwise or counter-clockwise).

Not wishing to be bound by theory, FIG. 6 is a cross-sectional view of the expanding channel 234 of a chamber lid 232 showing simplified representations of two gas flows therethrough. Although the exact flow pattern through the expanding channel 234 is not known, it is believed that the circular flow 310 (FIG. 6) may travel as a “vortex,” “helix,” or “spiral” flow 402A, 402B through the expanding channel 234 as shown by arrows 402A, 402B. As shown in FIG. 6, the circular flow may be provided in a “processing region” as opposed to in a compartment separated from the substrate 210. In one aspect, the vortex flow may help to establish a more efficient purge of the expanding channel 234 due to the sweeping action of the vortex flow pattern across the inner surface of the expanding channel 234.

In one embodiment, the distance 410 between the gas inlets 236A, 236B and the substrate 210 is made far enough that the “vortex” flow 402 dissipates to a downwardly flow as shown by arrows 404 as a spiral flow across the surface of the substrate 210 may not be desirable. It is believed that the “vortex” flow 402 and the downwardly flow 404 proceeds in a laminar manner efficiently purging the chamber lid 232 and the substrate 210. In one specific embodiment the distance 410 between the upper portion 237 of the expanding channel 234 and the substrate 210 is about 1.0 inches or more, more preferably about 2.0 inches or more. In one specific embodiment, the upper limit of the distance 410 is dictated by practical limitations. For example, if the distance 410 is very long, then the residence time of a gas traveling through the expanding channel 234 would be long, then the time for a gas to deposit onto the substrate would be long, and then throughput would be low. In addition, if distance 410 is very long, manufacturing of the expanding channel 234 would be difficult. In general, the upper limit of distance 410 may be 3 inches or more for a chamber adapted to process 200 mm diameter substrates or 5 inches or more for a chamber adapted to process 300 mm diameter substrates.

Referring to FIG. 1, at least a portion of the bottom surface 260 of the chamber lid 232 may be tapered from the expanding channel 234 to a peripheral portion of the chamber lid 232 to help provide an improved velocity profile of a gas flow from the expanding channel 234 across the surface of the

substrate **210** (i.e., from the center of the substrate to the edge of the substrate). The bottom surface **260** may comprise one or more tapered surfaces, such as a straight surface, a concave surface, a convex surface, or combinations thereof. In one embodiment, the bottom surface **260** is tapered in the shape of a funnel.

Not wishing to be bound by theory, FIG. 7 is schematic view illustrating the flow of a gas at two different positions **502**, **504** between the bottom surface **260** of the chamber lid **232** and the surface of a substrate **210**. The velocity of the gas at a certain position is theoretically determined by the equation below:

$$Q/A=V \quad (1)$$

In which, "Q" is the flow of the gas, "A" is the area of the flow section, and "V" is the velocity of the gas. The velocity of the gas is inversely proportional to the area "A" of the flow section ($H \times 2\pi R$), in which "H" is the height of the flow section and " $2\pi R$ " is the circumference of the flow section. In other words, the velocity of a gas is inversely proportional to the height "H" of the flow section and the radius "R" of the flow section.

Comparing the velocity of the flow section at position **502** and position **504**, assuming that the flow "Q" of the gas at all positions between the bottom surface **260** of the chamber lid **232** and the surface of the substrate **210** is equal, the velocity of the gas may be theoretically made equal by having the area "A" of the flow sections equal. For the area of flow sections at position **502** and position **504** to be equal, the height H_1 at position **502** must be greater than the height H_2 .

In one aspect, the bottom surface **260** is downwardly sloping to help reduce the variation in the velocity of the gases as it travels between the bottom surface **260** of the chamber lid **232** and the substrate **210** to help provide uniform exposure of the surface of the substrate **210** to a reactant gas. In one embodiment, the ratio of the maximum area of the flow section over the minimum area of the flow section between a downwardly sloping bottom surface **260** of the chamber lid **232** and the surface of the substrate **210** is preferably less than about 2, more preferably less than about 1.5, more preferably less than about 1.3, and most preferably about 1.

Not wishing to be bound by theory, it is believed that a gas flow traveling at a more uniform velocity across the surface of the substrate **210** helps provide a more uniform deposition of the gas on the substrate **210**. It is believed that the velocity of the gas is directly proportional to the concentration of the gas which is in turn directly proportional to the deposition rate of the gas on the substrate surface. Thus, a higher velocity of a gas at a first area of the surface of the substrate versus a second area of the surface of the substrate is believed to provide a higher deposition of the gas on the first area. It is believed that a chamber lid having a downwardly sloping bottom surface **260** provides for more uniform deposition of the gas across the surface of the substrate because the downwardly sloping bottom surface provides a more uniform velocity and, thus, a more uniform concentration of the gas across the surface of the substrate.

Referring to FIG. 1, the chamber lid **232** may have a choke **262** at a peripheral portion of the chamber lid **232** adjacent the periphery of the substrate **210**. The choke **262**, when the chamber lid **232** is assembled to form a processing zone around the substrate **210**, comprises any member restricting the flow of gas therethrough at an area adjacent the periphery of the substrate **210**. FIG. 9A is a schematic cross-sectional view of one embodiment of the choke **262**. In this embodiment, the choke **262** comprises a circumferential lateral portion **267**. In one aspect, the purge ring **222** may be adapted to

direct a purge gas toward the lateral portion **267** of the choke **262**. FIG. 9B is a schematic cross-sectional view of another embodiment of the choke **262**. In this embodiment, the choke **262** comprises a circumferential downwardly extending protrusion **268**. In one aspect, the purge ring **222** may be adapted to direct a purge gas toward the circumferential downwardly extending protrusion **268**. In one specific embodiment, the thickness of the downwardly extending protrusion **268** is between about 0.01 inches and about 1.0 inch, more preferably 0.01 inches and 0.5 inches.

In one specific embodiment, the spacing between the choke **262** and the substrate support **212** is between about 0.04 inches and about 2.0 inches, and preferably between 0.04 inches and about 0.2 inches. The spacing may vary depending on the gases being delivered and the process conditions during deposition. The choke **262** helps provide a more uniform pressure distribution within the volume or a reaction zone **264** defined between the chamber lid **232** and the substrate **210** by isolating the reaction zone **264** from the non-uniform pressure distribution of the pumping zone **266** (FIG. 1).

Referring to FIG. 1, in one aspect, since the reaction zone **264** is isolated from the pumping zone **266**, a reactant gas or purge gas needs only adequately fill the reaction zone **264** to ensure sufficient exposure of the substrate **210** to the reactant gas or purge gas. In conventional chemical vapor deposition, prior art chambers are required to provide a combined flow of reactants simultaneously and uniformly to the entire surface of the substrate in order to ensure that the co-reaction of the reactants occurs uniformly across the surface of the substrate. In atomic layer deposition, the present chamber **200** sequentially introduces reactants to the substrate surface to provide absorption of alternating thin layers of the reactants onto the surface of the substrate. As a consequence, atomic layer deposition does not require a flow of a reactant which reaches the surface of the substrate simultaneously. Instead, a flow of a reactant needs to be provided in an amount which is sufficient to absorb a thin layer of the reactant on the surface of the substrate.

Since the reaction zone **264** may comprise a smaller volume when compared to the inner volume of a conventional CVD chamber, a smaller amount of gas is required to fill the reaction zone **264** for a particular process in an atomic layer deposition sequence. For example, in one embodiment, the volume of the reaction zone **264** is about 1000 cm^3 or less, preferably 500 cm^3 or less, and more preferably 200 cm^3 or less for a chamber adapted to process 200 mm diameter substrates. In one embodiment, the volume of the reaction zone **264** is about $3,000 \text{ cm}^3$ or less, preferably $1,500 \text{ cm}^3$ or less, and more preferably 600 cm^3 or less for a chamber adapted to process 300 mm diameter substrates. In one embodiment, the substrate support **212** may be raised or lowered to adjust the volume of the reaction zone **264** for deposition. Because of the smaller volume of the reaction zone **264**, less gas, whether a deposition gas or a purge gas, is necessary to be flowed into the chamber **200**. Therefore, the throughput of the chamber **200** is greater and the waste may be minimized due to the smaller amount of gas used reducing the cost of operation.

The chamber lid **232** has been shown as comprising a cap portion **272** and a chamber plate portion **270** in which the cap portion **272** and the chamber plate portion **270** form the expanding channel **234**. An additional plate may be optionally disposed between the chamber lid portion **270** and the cap portion **272**. In other embodiments, the expanding channel **234** may be made integrally from a single piece of material.

The chamber lid **232** may include cooling elements and/or heating elements depending on the particular gas being deliv-

ered therethrough. Controlling the temperature of the chamber lid **232** may be used to prevent gas decomposition, deposition, or condensation on the chamber lid **232**. For example, water channels may be formed in the chamber lid **232** to cool the chamber lid **232**. In another example, heating elements may be embedded or may surround components of the chamber lid **232** to heat the chamber lid **232**. In one embodiment, components of the chamber lid **232** may be individually heated or cooled. For example, referring to FIG. 1, the chamber lid **232** may comprise a chamber plate portion **270** and a cap portion **272** in which the chamber plate portion **270** and the cap portion **272** form the expanding channel **234**. The cap may be maintained at one temperature range and the chamber lid may be maintained at another temperature range. For example, the cap **272** may be heated by being wrapped in heater tape or by using another heating device to prevent condensation of reactant gases and the chamber plate portion **270** may be maintained at ambient temperature. In another example, the cap **272** may be heated and the chamber plate portion may be cooled with water channels formed therethrough to prevent thermal decomposition of reactant gases on the chamber plate portion **270**.

The chamber lid **232** may be made of stainless steel, aluminum, nickel-plated aluminum, nickel, or other suitable materials compatible with the processing to be performed. In one embodiment, the cap portion **272** comprises stainless steel and the chamber plate portion **270** comprises aluminum. In one embodiment, the additional plate comprises stainless steel. In one embodiment, the expanding channel **234** and the bottom surface **260** of the chamber lid **232** may comprise a mirror polished surface to help produce a laminar flow of a gas along the expanding channel **234** and the bottom surface **260** of the chamber lid **232**. In another embodiment, the inner surface of the gas conduits **250A**, **250B** may be electropolished to help produce a laminar flow of a gas therethrough.

Returning to FIG. 1, a control unit **280**, such as a programmed personal computer, work station computer, or the like, may be coupled to the chamber **200** to control processing conditions. For example, the control unit **280** may be configured to control flow of various process gases and purge gases from gas sources **238**, **239**, **240** through the valves **242A**, **242B** during different stages of a substrate process sequence. Illustratively, the control unit **280** comprises a central processing unit (CPU) **282**, support circuitry **284**, and memory **286** containing associated control software **283**.

The control unit **280** may be one of any form of general purpose computer processor that can be used in an industrial setting for controlling various chambers and sub-processors. The CPU **282** may use any suitable memory **286**, such as random access memory, read only memory, floppy disk drive, hard disk, or any other form of digital storage, local or remote. Various support circuits may be coupled to the CPU **282** for supporting the chamber **200**. The control unit **280** may be coupled to another controller that is located adjacent individual chamber components, such as the programmable logic controllers **248A**, **248B** of the valves **242A**, **242B**. Bi-directional communications between the control unit **280** and various other components of the chamber **200** are handled through numerous signal cables collectively referred to as signal buses **288**, some of which are illustrated in FIG. 1. In addition to control of process gases and purge gases from gas sources **238**, **239**, **240** and from the programmable logic controllers **248A**, **248B** of the valves **242A**, **242B**, the control unit **280** may be configured to be responsible for automated control of other activities used in wafer processing—such as

wafer transport, temperature control, chamber evacuation, among other activities, some of which are described elsewhere herein.

In operation, a substrate **210** is delivered to the chamber **200** through the opening **208** by a robot (not shown). The substrate **210** is positioned on the substrate support **212** through cooperation of the lift pins **220** and the robot. The substrate support **212** raises the substrate **210** into close opposition to the bottom surface **260** of the chamber lid **232**. A first gas flow may be injected into the expanding channel **234** of the chamber **200** by valve **242A** together or separately (i.e. pulses) with a second gas flow injected into the chamber **200** by valve **242B**. The first gas flow may comprise a continuous flow of a purge gas from purge gas source **240** and pulses of a reactant gas from reactant gas source **238** or may comprise pulses of a reactant gas from reactant gas source **238** and pulses of a purge gas from purge gas source **240**. The second gas flow may comprise a continuous flow of a purge gas from purge gas source **240** and pulses of a reactant gas from reactant gas source **239** or may comprise pulses of a reactant gas from reactant gas source **239** and pulses of a purge gas from purge gas source **240**. The gas flow travels through the expanding channel **234** as a vortex flow pattern **402** which provides a sweeping action across the inner surface of the expanding channel **234**. The vortex flow pattern **402** dissipates to a downwardly flow **404** toward the surface of the substrate **210**. The velocity of the gas flow reduces as it travels through the expanding channel **234**. The gas flow then travels across the surface of the substrate **210** and across the bottom surface **260** of the chamber lid **232**. The bottom surface **260** of the chamber lid **232**, which is downwardly sloping, helps reduce the variation of the velocity of the gas flow across the surface of the substrate **210**. The gas flow then travels by the choke **262** and into the pumping zone **266** of the chamber **200**. Excess gas, by-products, etc. flow into the pumping channel **279** and are then exhausted from the chamber **200** by a vacuum system **278**. In one aspect, the gas flow proceeds through the expanding channel **234** and between the surface of the substrate **210** and the bottom surface **260** of the chamber lid **232** in a laminar manner which aids in uniform exposure of a reactant gas to the surface of the substrate **210** and efficient purging of inner surfaces of the chamber lid **232**.

Chamber **200** has been described herein as having a combination of features. In one aspect, chamber **200** provides a reaction zone comprising a small volume in compared to a conventional CVD chamber. The chamber **200** requires a smaller amount of a gas, such as a reactant gas or a purge gas, to fill the reaction zone for a particular process. In another aspect, chamber **200** provides a chamber lid having a downwardly sloping or funnel shaped bottom surface to reduce the variation in the velocity profile of a gas flow traveling between the bottom surface of the chamber lid and a substrate. In still another aspect, the chamber **200** provides an expanding channel to reduce the velocity of a gas flow introduced therethrough. In still another aspect, the chamber **200** provides gas conduits at an angle α from the center of the expanding channel. The chamber **200** provides other features as described elsewhere herein. Other embodiments of a chamber adapted for atomic layer deposition incorporate one or more of these features.

For example, FIG. 8 shows another embodiment of a chamber **800** including a gas delivery apparatus **830** comprising a chamber lid **832** which provides a reaction zone comprising a small volume and which provides an expanding channel. Some components of the chamber **800** are the same or similar to those described with reference to chamber **200** of FIG. 1, described above. Accordingly, like numbers have been used

where appropriate. The chamber lid **832** comprises a bottom surface **860** that is substantially flat. In one embodiment, the spacing between the choke **262** and the substrate support **210** is between about 0.04 inches and about 2.0 inches, more preferably between about 0.04 inches and about 0.2 inches.

The gas delivery apparatus **230** of FIG. **1** has been described as including two valves **242A**, **242B** coupled to a reactant gas source and a purge gas source. In other embodiments, the gas delivery apparatus **230** may comprise one or more valves coupled to a single or a plurality of gas sources in a variety of configurations. FIGS. **1**, **5**, and **6** show a chamber **200** adapted to provide two gas flows together or separately from two gas inlets **236A**, **236B** utilizing two valves **242A**, **242B**.

The processing chamber **200** may be integrated into an integrated processing platform, such as an Endura™ platform also available from Applied Materials, Inc. Details of the Endura™ platform are described in commonly assigned U.S. patent application Ser. No. 09/451,628, entitled "Integrated Modular Processing Platform", filed on Nov. 30, 1999, which is incorporated by reference herein.

The chamber **200** includes a chamber body **202** having a slit valve **208** formed in a sidewall **204** thereof and a substrate support **212** disposed therein. The substrate support **212** is mounted to a lift motor **214** to raise and lower the substrate support **212** and a substrate **210** disposed thereon. The substrate support **212** may also include a vacuum chuck, an electrostatic chuck, or a clamp ring for securing the substrate **212** to the substrate support **212** during processing. Further, the substrate support **212** may be heated using an embedded heating element, such as a resistive heater, or may be heated using radiant heat, such as heating lamps disposed above the substrate support **212**. A purge ring **222** may be disposed on the substrate support **212** to define a purge channel **224** that provides a purge gas to prevent deposition on a peripheral portion of the substrate **210**.

A gas delivery apparatus **230** is disposed at an upper portion of the chamber body **202** to provide a gas, such as a process gas and/or a purge gas, to the chamber **200**. A vacuum system **278** is in communication with a pumping channel **279** to evacuate gases from the chamber **200** and to help maintain a desired pressure or a desired pressure range inside a pumping zone **266** of the chamber **200**.

The gas delivery apparatus **230** includes a chamber lid **232** having an expanding channel **234** formed within a central portion thereof. The chamber lid **232** also includes a bottom surface **260** extending from the expanding channel **234** to a peripheral portion of the chamber lid **232**. The bottom surface **260** is sized and shaped to substantially cover the substrate **210** disposed on the substrate support **212**. The expanding channel **234** has an inner diameter that gradually increases from an upper portion **237** to a lower portion **235** adjacent the bottom surface **260** of the chamber lid **232**. The velocity of a gas flowing therethrough decreases as the gas flows through the expanding channel **234** due to the expansion of the gas. The decreased gas velocity reduces the likelihood of blowing off reactants adsorbed on the surface of the substrate **210**.

The gas delivery apparatus **230** also includes at least two high speed actuating valves **242** having one or more ports. At least one valve **242** is dedicated to each reactive compound. For example, a first valve is dedicated to a refractory metal-containing compound, such as tantalum and titanium, and a second valve is dedicated to a nitrogen-containing compound. When a ternary material is desired, a third valve is dedicated to an additional compound, such as a silicon-containing compound if a silicide is desired.

The valves **242** may generally be any type of valve capable of reliably, repeatedly, and precisely metering the desired precursors at the desired rate of introduction. In some cases, dosing may be as fast as 1-2 milliseconds (msec). As one example, the valves **242** may be electronically controlled (EC) valves, which are commercially available from Fujikin of Japan as part number FR-21-6.35 UGF-APD. The valves **242** precisely and repeatedly deliver short pulses of the reactive compounds into the chamber body **202**. The on/off cycles or pulses of the valves **242** are less than about 100 msec. The valves **242** can be directly controlled by a system computer, such as a mainframe for example, or controlled by a chamber/application specific controller, such as a programmable logic computer (PLC) which is described in more detail in the co-pending U.S. patent application Ser. No. 09/800,881, entitled "Valve Control System For ALD Chamber", filed on Mar. 7, 2001, which is incorporated by reference herein.

An exemplary process for forming a TaN barrier layer on a 200 mm wafer using a cyclical deposition process of alternate/sequential pulses of PDMAT and ammonia is described below. The process may be performed within a processing chamber, such as the processing chamber **200** described in FIG. **1**. PDMAT is a preferred tantalum-containing compound for a number of reasons. PDMAT is relatively stable, and has a vapor pressure which makes it easy to deliver. PDMAT may also be produced with a low halide content, such as less than 100 ppm, and may even be produced with a halide content of less than 30 ppm or even less than 5 ppm. Not wishing to be bound by theory, it is believed that an organo-metallic precursor with a low halide content is beneficial because halides (such as chlorine) incorporated in the barrier layer may attack the copper layer deposited thereover.

To deposit the TaN layer, an inert/purge gas such as argon is first introduced into the processing chamber **200** to stabilize the pressure and temperature therein. This separate flow of gas flows continuously during the deposition process such that only the separate flow of gas flows between pulses of each compound. After the chamber pressure and temperature have been stabilized between about 200° C. and about 300° C. at about 1 Torr to about 5 Torr, a first pulse of PDMAT is provided from the gas source **238** at a flow rate between about 100 sccm and about 400 sccm, with a pulse time of about 0.6 seconds or less. A pulse of ammonia is then provided from the gas source **239** at a flow rate between about 200 sccm and about 600 sccm, with a pulse time of about 0.6 seconds or less.

A pause between pulses of PDMAT and ammonia is about 1.0 second or less, about 0.5 seconds or less, or about 0.1 seconds or less. A pause after the pulse of ammonia is also about 1.0 second or less, about 0.5 seconds or less, or about 0.1 seconds or less. Argon gas flowing between about 100 sccm and about 1,000 sccm, such as between about 100 sccm and about 400 sccm, is continuously provided from the gas source **240** through each valve **242**. In one aspect, at least a portion of a pulse of PDMAT may still be in the chamber when at a least a portion of a pulse of ammonia enters so that some co-reaction or gas phase co-reaction takes place. In another aspect, the duration of the purge gas and/or pump evacuation is designed to prevent the pulses of PDMAT and ammonia from mixing together in the reaction zone.

The heater temperature is maintained between about 100° C. and about 300° C. at a chamber pressure between about 1.0 and about 5.0 Torr. Each cycle consisting of a pulse of PDMAT, pause, pulse of ammonia, and pause provides a tantalum nitride layer having a thickness between about 0.3 Å and about 1.0 Å per cycle. The alternating sequence may be repeated until the desired thickness is achieved, which is less

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than about 20 Å, such as about 10 Å. Accordingly, the deposition method requires between 10 and 70 cycles, more typically between 20 and 30 cycles.

A similar deposition method is used to deposit a barrier layer consisting of titanium silicon nitride. Each cycle consists of a pulse of a titanium-containing compound, a pause, a pulse of a silicon-containing compound, a pause, a pulse of a nitrogen-containing compound, and a pause. In one aspect, each cycle consists of a pulse of TDMAT, a first pause, a pulse of silane, a second pause, a pulse of ammonia, and a third pause.

To initiate the cyclical deposition of a Ti_xSi_yN layer, argon is introduced into the processing chamber 200 to stabilize the chamber pressure between about 1 Torr and about 5 Torr and the chamber temperature between about 200° C. and about 300° C. This separate flow of argon flows continuously during the deposition process such that only the argon flows between pulses of each compound. The separate flow of argon flows between about 100 sccm and about 1,000 sccm, such as between about 100 sccm and about 400 sccm.

After the chamber pressure and temperature have been stabilized at about 250° C. and 5 Torr, a pulse of TDMAT is provided at a flow rate between about 10 sccm and about 1,000 sccm, with a pulse time of about 0.6 seconds or less. A pulse of silane is then provided at a flow rate between about 5 sccm and about 500 sccm, with a pulse time of about 1 second or less. A pulse of ammonia is then provided at a flow rate between about 100 sccm and about 5,000 sccm, with a pulse time of about 0.6 seconds or less.

A pause between pulses of TDMAT and silane is about 1.0 second or less, about 0.5 seconds or less, or about 0.1 seconds or less. A pause between pulses of silane and ammonia is about 1.0 second or less, about 0.5 seconds or less, or about 0.1 seconds or less. A pause after the pulse of ammonia is also about 1.0 second or less, about 0.5 seconds or less, or about 0.1 seconds or less. In one aspect, a pulse of TDMAT may still be in the chamber when a pulse of silane enters, and a pulse of silane may still be in the chamber when a pulse of ammonia enters.

The heater temperature is maintained between about 100° C. and about 300° C. at a chamber pressure between about 1.0 and about 5.0 Torr. Each cycle consisting of a pulse of TDMAT, pause, pulse of silane, pause, pulse of ammonia, and pause provides a titanium silicon nitride layer having a thickness between about 0.3 Å and about 1.0 Å per cycle. The alternating sequence may be repeated until the desired thickness is achieved, which is less than about 20 Å, such as about 10 Å. Accordingly, the deposition method requires between 10 and 70 cycles.

FIGS. 2A-2D are cross sectional views of a wafer at different stages of a multi-layer metal interconnect fabrication sequence incorporating a thin barrier layer deposited using a cyclical deposition process described herein. FIG. 2A shows a lower level metal interconnect 110 having a dielectric layer 112 formed thereon. The dielectric layer 112 may be any dielectric material including a low k dielectric material, whether presently known or yet to be discovered. For example, the dielectric layer 112 may be a silicon oxide or a carbon doped silicon oxide, for example. The dielectric layer 112 has been etched to form a feature 114 therein using conventional and well-known techniques. The feature 114 may be a plug, via, contact, line, wire, or any other interconnect facet. The feature 114 has vertical sidewalls 116 and a bottom 118, typically having an aspect ratio of 4:1 or greater, such as 6:1. The bottom 118 exposes at least a portion of the lower level metal interconnect 110.

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Referring to FIG. 2B, a barrier layer 130 is deposited using the techniques described above on the bottom 118 as well as the side walls 116 of the feature 114. The barrier layer 130 has a thickness less than about 20 Å, preferably about 10 Å. The barrier layer may be a binary material or a ternary material as discussed above.

Optionally, the patterned or etched substrate dielectric layer 112 may be cleaned to remove native oxides or other contaminants from the surface thereof prior to depositing the barrier layer 130. For example, reactive gases may be excited into a plasma within a remote plasma source chamber and delivered to the processing chamber 200. An exemplary remote plasma chamber is a Reactive Pre-clean II chamber available from Applied Materials, Inc., located in Santa Clara, Calif. Alternatively, the processing chamber 200 may be modified to deliver the pre-cleaning gas plasma through existing gas inlets.

In one aspect, the reactive pre-clean process forms radicals from a plasma of one or more reactive gases such as argon, helium, hydrogen, nitrogen, fluorine-containing compounds, and combinations thereof. For example, a reactive gas may include a mixture of tetrafluorocarbon (CF_4) and oxygen (O_2), or a mixture of helium (He) and nitrogen trifluoride (NF_3).

The plasma is typically generated by applying a power of about 500 to 2,000 watts RF at a frequency of about 200 KHz to 114 MHz. The flow of reactive gases ranges between about 100 and about 1,000 sccm and the plasma treatment lasts for about 10 to about 150 seconds. Preferably, the plasma is generated in one or more treatment cycles and purged between cycles. For example, four treatment cycles lasting 35 seconds each is effective.

In another aspect, the patterned or etched dielectric layer 112 may be pre-cleaned first using an argon plasma and then a hydrogen plasma. A processing gas having greater than about 50% argon by number of atoms is introduced at a pressure of about 0.8 mTorr. A plasma is struck to subject the dielectric layer 112 to an argon sputter cleaning environment. The argon plasma is preferably generated by applying between about 50 watts and about 500 watts of RF power. The argon plasma is maintained for between about 10 seconds and about 300 seconds to provide sufficient cleaning time for the deposits that are not readily removed by a reactive hydrogen plasma. Following the argon plasma, the chamber pressure is increased to about 140 mTorr, and a processing gas consisting essentially of hydrogen and helium is introduced into the processing region. Preferably, the processing gas comprises about 5% hydrogen and about 95% helium. The hydrogen plasma is generated by applying between about 50 watts and about 500 watts power. The hydrogen plasma is maintained for about 10 seconds to about 300 seconds.

Referring to FIGS. 2C and 2D, a metal, metal alloy, or a combination thereof is deposited over the barrier layer 130 to at least partially fill the feature 114. In one aspect, a metal seed layer 140 of a copper-containing material is first deposited having a thickness of about 1,000 Å to about 2,000 Å. Next, a copper metal layer 142 is deposited over the seed layer 140 to fill the feature 114.

In one aspect, the copper-containing seed layer 140 is deposited using high density plasma physical vapor deposition (HDP-PVD) to enable good conformal coverage. One example of a HDP-PVD chamber is the Ionized Metal Plasma (IMP) Vectra™ chamber, available from Applied Materials, Inc. of Santa Clara, Calif. The IMP chamber may also be integrated into an Endura™ platform, also available from Applied Materials, Inc. Of course, other techniques, such as

physical vapor deposition, chemical vapor deposition, electroless plating, and electroplating, may be used.

The IMP chamber includes a target, coil, and biased substrate support member. To form the copper seed layer **140**, a power between about 0.5 kW and about 5 kW is applied to the target, and a power between about 0.5 kW and 3 kW is applied to the coil. A power between about 200 and about 500 W at a frequency of about 13.56 MHz is applied to bias the substrate. Argon is flowed into the chamber at a rate of about 35 sccm to about 85 sccm, and nitrogen may be added to the chamber at a rate of about 5 sccm to about 100 sccm. The substrate support member is heated to a temperature between about 50° C. and 250° C. as the pressure of the chamber is typically between about 5 mTorr to about 100 mTorr.

Referring to FIG. 2D, the copper metal layer **142** may be deposited over the copper seed layer **140** using CVD, PVD, electroless, or electroplating techniques. In one aspect, the copper layer **142** is formed using an electroplating cell, such as the Electra™ Cu ECP system, available from Applied Materials, Inc., of Santa Clara, Calif. The Electra™ Cu ECP system may also be integrated into an Endura™ platform also available from Applied Materials, Inc. A copper electrolyte solution and copper electroplating technique is described in commonly assigned U.S. Pat. No. 6,113,771, entitled "Electro-deposition Chemistry", which is incorporated by reference herein. Typically, the electroplating bath has a copper concentration greater than about 0.7M, a copper sulfate concentration of about 0.85, and a pH of about 1.75. The electroplating bath may also contain various additives as is well known in the art. The temperature of the bath is between about 15° C. and about 25° C. The bias is between about -15 volts to about 15 volts. In one aspect, the positive bias ranges from about 0.1 volts to about 10 volts and the negative bias ranges from about -0.1 to about -10 volts.

Optionally, an anneal treatment may be performed following copper deposition whereby the wafer is subjected to a temperature between about 100° C. and about 400° C. for about 10 minutes to about 1 hour, preferably about 30 minutes. A non-reactive gas such as helium, hydrogen, nitrogen, or a mixture thereof is introduced at a rate of 100 to about 10,000 sccm. The chamber pressure is maintained between about 2 Torr and about 10 Torr. The RF power is about 200 W to about 1,000 W at a frequency of about 13.56 MHz, and the preferable substrate spacing is between about 300 mils and about 800 mils.

Following deposition, the top portion of the resulting structure may be planarized following the copper metal deposition. A chemical mechanical polishing (CMP) apparatus may be used, such as the Mirra™ System available from Applied Materials, Santa Clara, Calif., for example. For example, portions of the copper **140** and the dielectric **112** are removed from the top of the structure leaving a fully planar surface. Optionally, the intermediate surfaces of the structure may be planarized between the deposition of the subsequent layers described above.

As stated above, the processing steps of the embodiments described herein may be performed in an integrated processing platform such as the Endura™ platform available from Applied Materials, Inc. of Santa Clara, Calif. To facilitate the control and automation of the overall system, the integrated processing system may include a controller **140** comprising a central processing unit (CPU) **142**, memory **144**, and support circuits **146**. The CPU **142** may be one of any form of computer processors that are used in industrial settings for controlling various drives and pressures. The memory **144** is connected to the CPU **142**, and may be one or more of a readily available memory such as random access memory

(RAM), read only memory (ROM), floppy disk, hard disk, or any other form of digital storage, local or remote. Software instructions and data can be coded and stored within the memory **144** for instructing the CPU **142**. The support circuits **146** are also connected to the CPU **142** for supporting the processor **142** in a conventional manner. The support circuits **146** may include cache, power supplies, clock circuits, input/output circuitry, subsystems, and the like.

FIG. 3 is a transmission electron microscope (TEM) image of a feature **300** having a titanium nitride barrier layer **310** deposited therein according to the deposition techniques described above. The feature **300** had an aspect ratio of 5:1 and was formed on a 200 mm wafer. The barrier layer **310** consisted of tantalum nitride and was deposited at 250° C. and 2 Torr. Each cycle lasted about 2 seconds and 30 cycles were performed. The tantalum nitride barrier layer **310** had a thickness of about 15 angstroms. As shown, the barrier layer **310** is conformal and shows good step coverage throughout the entire feature **300**.

FIG. 4 is a TEM image showing a partial cross sectional view of a multi-level, interconnect structure **400**. The multi-level, interconnect structure **400** included a lower level copper interconnect **405**, a tantalum nitride barrier layer **410**, and an upper level copper interconnect **420**. As shown, the copper grain growth of the lower level copper interconnect **405** extended across the barrier layer **410** into the upper level copper interconnect **420**. The barrier layer **410** consisted of tantalum nitride and was deposited at 250° C. and 2 Torr. Each cycle lasted about 2 seconds and 30 cycles were performed. The barrier layer **410** had a thickness of about 10 angstroms, which was sufficient to inhibit copper migration into the dielectric material, but not establish a growth pattern of its own.

It is believed that a refractory metal nitride layer having a thickness greater than about 20 angstroms will terminate the growth pattern of the lower level metal interconnect. A refractory metal nitride layer having a thickness of about 20 angstroms or more will establish a distinct growth pattern of its own, which would be initially adopted by the higher interconnect until the higher interconnect reaches a particular thickness and establishes its own pattern, thereby forming a different crystal structure. This phenomenon occurs because a growth pattern of a subsequently deposited layer typically resembles a growth pattern of an underlying layer during its initial stages of deposition, but the subsequent layer then takes on its own, inherent pattern once the subsequent layer reaches a particular thickness.

Tantalum nitride, for example, has a natural inclination to form an amorphous structure at about 20 angstroms or more. Below about 20 angstroms, TaN resembles the growth pattern of its underlying layer. Therefore, a subsequent copper interconnect layer was surprisingly grown across a barrier layer deposited according to the methods of the present invention exhibiting a similar growth pattern as the underlying copper interconnect.

The barrier layers **310**, **410** shown and described with reference to FIGS. 3 and 4 were measured using a TEM instrument. It can be appreciated that a margin of error is present with this kind of measurement technique as well as any other measurement technique for determining a thickness of a deposited layer. Therefore, the thicknesses provided herein are approximate and quantified according to the best available known techniques and are not intended to limit the scope of the present invention.

While the foregoing is directed to embodiments of the present invention, other and further embodiments of the

invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

The invention claimed is:

1. A method for processing a substrate, comprising:
 - precleaning a dielectric layer on a substrate;
 - positioning the substrate in a chamber, the chamber having a chamber lid having an expanding channel, a bottom surface coupled with the expanding channel, and one or more gas conduits coupled with the expanding channel, wherein each of the one or more gas conduits is connected to a sidewall of the expanding channel and is positioned in a non-linear manner with respect to a center of the expanding channel and to other gas conduits to introduce a process gas into the expanding channel in a vortex, helix, or spiral flow pattern, and wherein the bottom surface is tapered from the expanding channel to a peripheral portion of the chamber lid and is sized and shaped to substantially cover the substrate;
 - forming a barrier layer on the substrate by flowing the process gas into the expanding channel in a manner to form the vortex, helix, or spiral flow pattern which provides a sweeping action across an inner surface of the expanding channel, the vortex, helix, or spiral flow pattern being dissipated while traveling through the expanding channel to a downwardly gas flow toward and across a surface of the substrate in a laminar manner, and sequentially pulsing reagents into the gas during an atomic layer deposition, wherein the atomic layer deposition comprises introducing one or more pulses of a metal-containing precursor and a nitrogen-containing precursor to the expanding channel; and
 - depositing a seed layer on the barrier layer.
2. The method of claim 1, wherein the nitrogen-containing precursor is selected from the group consisting of nitrogen gas, ammonia, hydrazine, methylhydrazine, dimethylhydrazine, t-butylhydrazine, phenylhydrazine, azotertbutane, ethylazide, derivatives thereof, and combinations thereof.
3. The method of claim 1, wherein the metal-containing precursor is selected from the group consisting of pentaethyl methylamino-tantalum (PEMAT), pentadiethylamino-tantalum (PDEAT), pentadimethylamino-tantalum (PDMAT), t-butylimino tris(diethylamino)tantalum (TBTDET), t-butylimino tris(dimethylamino)tantalum (TBTDMT), bis(cyclopentadienyl)tantalum trihydride, bis(methylcyclopentadienyl)tantalum trihydride, tantalum fluoride, tantalum bromide, tantalum chloride, derivatives thereof, and combinations thereof.
4. The method of claim 1, wherein the metal-containing precursor is selected from the group consisting of tetrakis(dimethylamino)titanium (TDMAT), tetrakis(ethylmethylamino)titanium (TEMAT), tetrakis(diethylamino)titanium (TDEAT), titanium tetrachloride (TiCl₄), titanium iodide (TiI₄), titanium bromide (TiBr₄), and derivatives thereof.
5. The method of claim 1, wherein the atomic layer deposition further comprises:
 - alternately pulsing a metal-containing precursor, a silicon-containing precursor, and a nitrogen-containing precursor until a refractory metal silicon nitride layer having a thickness less than about 20 angstroms is deposited over at least a portion of a substrate surface.
6. The method of claim 5, wherein the silicon-containing precursor is selected from the group consisting of silane, disilane, methylsilane, dimethylsilane, chlorosilane (SiH₃Cl), dichlorosilane (SiH₂Cl₂), trichlorosilane (SiHCl₃), and combinations thereof.

7. A method for processing a substrate, comprising:
 - precleaning a dielectric layer on a substrate;
 - positioning the substrate in a chamber, the chamber having a chamber lid having an expanding channel, a bottom surface coupled with the expanding channel, and a plurality of gas conduits coupled to a sidewall of the expanding channel, wherein each gas conduit is positioned in a non-linear manner with respect to a center of the expanding channel and to other gas conduits to introduce a process gas into the expanding channel in a circular flow pattern, and the bottom surface is tapered from the expanding channel to a peripheral portion of the chamber lid and is sized and shaped to substantially cover the substrate;
 - forming a barrier layer on the substrate by flowing the process gas into the expanding channel in a manner to form the circular flow pattern which provides a sweeping action across an inner surface of the expanding channel, the circular flow pattern being dissipated while traveling through the expanding channel to a downwardly gas flow toward and across a surface of the substrate in a laminar manner, and sequentially pulsing reagents into the gas during an atomic layer deposition, wherein the atomic layer deposition comprises introducing one or more pulses of a metal-containing precursor and a nitrogen-containing precursor to the expanding channel; and
 - depositing a seed layer on the barrier layer.
8. The method of claim 7, wherein the nitrogen-containing precursor is selected from the group consisting of nitrogen gas, ammonia, hydrazine, methylhydrazine, dimethylhydrazine, t-butylhydrazine, phenylhydrazine, azotertbutane, ethylazide, derivatives thereof, and combinations thereof.
9. The method of claim 7, wherein the metal-containing precursor is selected from the group consisting of pentaethyl methylamino-tantalum (PEMAT), pentadiethylamino-tantalum (PDEAT), pentadimethylamino-tantalum (PDMAT), t-butylimino tris(diethylamino)tantalum (TBTDET), t-butylimino tris(dimethylamino)tantalum (TBTDMT), bis(cyclopentadienyl)tantalum trihydride, bis(methylcyclopentadienyl)tantalum trihydride, tantalum fluoride, tantalum bromide, tantalum chloride, derivatives thereof, and combinations thereof.
10. The method of claim 7, wherein the metal-containing precursor is selected from the group consisting of tetrakis(dimethylamino)titanium (TDMAT), tetrakis(ethylmethylamino)titanium (TEMAT), tetrakis(diethylamino)titanium (TDEAT), titanium tetrachloride (TiCl₄), titanium iodide (TiI₄), titanium bromide (TiBr₄), and derivatives thereof.
11. The method of claim 7, wherein the atomic layer deposition further comprises:
 - alternately pulsing a metal-containing precursor, a silicon-containing precursor, and a nitrogen-containing precursor until a refractory metal silicon nitride layer having a thickness less than about 20 angstroms is deposited over at least a portion of a substrate surface, wherein the silicon-containing precursor is selected from the group consisting of silane, disilane, methylsilane, dimethylsilane, chlorosilane (SiH₃Cl), dichlorosilane (SiH₂Cl₂), trichlorosilane (SiHCl₃), and combinations thereof.
12. The method of claim 1, wherein the seed layer is a copper-containing seed layer.
13. The method of claim 1, wherein the seed layer has a thickness ranging from about 1,000 Å to about 2,000 Å.
14. The method of claim 1, wherein the barrier layer and the seed layer exhibit the same crystalline growth pattern.
15. The method of claim 1, wherein the barrier layer has a thickness ranging from about 10 Å to about 20 Å.

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16. The method of claim **1**, wherein the expanding channel has an inner diameter that gradually increases from an upper portion to a lower portion adjacent the tapered bottom surface.

17. The method of claim **1**, wherein the one or more gas conduits comprises two gas conduits being connected to the sidewall of the expanding channel.

18. The method of claim **17**, wherein the two gas conduits are positioned parallel to each other.

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19. The method of claim **17**, wherein each of the two gas conduits has an opening and is positioned about 180 degrees apart from one another.

20. The method of claim **19**, wherein the opening of the two gas conduits is located at the same elevation.

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